

IEEE P802.11 Wireless LANs

TGn Sync Proposal Technical Specification

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Abstract

This document presents the technical specification for the
MAC and the PHY layer of the TGn Sync proposal to IEEE 802.11 TGn

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1 Executive Summary

The TGn Sync team respectfully submits its complete proposal. The team is comprised of 802.11 WG participants whose companies represent a broad range of markets, including, PC, Enterprise, Consumer Electronics, Handset, Semiconductor and Public Access. Since these companies are based in the US, Europe and Asia Pacific, the team has had the benefit of a worldwide perspective, both in terms of perceived market demand as well as regulatory concerns (including channel bandwidth limitations, limited channel access, restricted transmission times, etc.).

Our goal has been to align (or “sync” with) 802.11n members to a single set of core positions prior to the TGn down selection phase. By aligning before entrenched positions form, we hope to increase the possibility of a more rapid introduction of an 802.11n standard.

The team has worked as a technical group for many months to develop a TGn proposal, recognizing that whatever decisions were made had to ultimately survive the TGn process and therefore be based solely on technical merit. There were no signed agreements involved in joining the TGn Sync team. There was no attempt to develop joint IP and each company was expected to abide by the same reasonable and non-discriminatory terms that the IEEE bylaws require.

The technical approach balances market expectations with design practicality. The solution is a robust, scalable architecture targeting the least amount of complexity. In fact, the basic configuration delivers a maximum rate of 243 Mbps using only two antennas. This rate is consistent with the historical trend of 5x with each generation of 802.11 (802.11/2Mbps, 802.11b/11Mbps, and finally 802.11a/ 54Mbps). The proposal also incorporates options for rates up to 720 Mbps. This choice of higher peak data rates was seen as critical for future proofing this next generation of WLAN.

The PHY techniques used to achieve the higher data rates involve a MIMO evolution of 802.11 OFDM PHY with spatial division multiplexing of spatial streams, wider bandwidth options (either 20MHz or 40MHz) and an optimized interleaver for both the 20 MHz and 40MHz channelizations. Additionally, optional enhancements include advanced FEC coding techniques (LDPC), space time block coding (STBC), and transmit beamforming with negligible additional cost in the receiving client device and/or additional RF chains. These options provide extra scalability if additional robustness and/or throughput is required.

The TGn Sync proposal also offers seamless interoperability with 802.11 legacy devices. This interoperability is achieved with an enhanced 802.11 preamble design and efficient PHY and MAC level mechanisms, which also provide robustness and cost-effectiveness.

The features added to improve MAC efficiency – for higher throughput and overall system performance – include aggregation, bi-directional data flow, enhanced Block Ack, channel management (including a receiver assisted channel training protocol) and feedback mechanisms that enable rate adaptation. Protection mechanisms are also added to achieve the seamless

interoperability and coexistence with legacy devices mentioned above. The approach supports 802.11e and proposes new features for further enhancement.

1.1 Proposal Structure

The TGn Sync complete proposal meets the IEEE 802.11n PAR, meets all functional requirements, and addresses all mandatory requirements of the comparison criteria.

This document contains a technical specification of the proposed MAC and PHY enhancements.

[5] contains the presentation of the proposal in powerpoint format. (Please note that the summary presentation [4] is no longer up to date).

[6] contains a statement of compliance to the IEEE 802.11 TGn FRCC requirements.

[7] and [8] contain FRCC results (and others) for the PHY and MAC respectively.

[9] and [10] are Excel spreadsheets containing detailed FRCC results from MAC simulations, and [11] describes the methodology used in these simulations.

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3 Definitions

Aggregate: A PSDU transported by the PHY with an aggregate attribute indicating that it contains multiple MPDUs.

Extended PHY Protection: A technique that uses the legacy signal field to protect from legacy transmission the contents of more than one HT format PPDU.

Initiator: A STA that holds a TXOP and transmits the first frame in a frame exchange sequence including aggregate PPDU and/or aggregate control frames (IAC/RAC/MRAD).

LongNAV: A MAC-layer protection mechanism that protects multiple PPDU exchanged within a TXOP

OFDM Format: Definition of subcarrier frequencies relative to the channel center frequency, and specification of data bearing and pilot subcarriers.

Originator: A QSTA that sends data using the Block ACK mechanism.

Preamble: short and long: Portions of the 802.11 HT PPDU used for PHY synchronization and channel estimation.

Receiver: Any STA receiving the current PPDU.

Recipient: A QSTA that receives data using the Block ACK mechanism.

Responder: A STA that responds to an initiator in a frame exchange sequence including aggregate PPDU and/or aggregate control frames.

Reverse Direction: Data flow from a responder to an initiator.

SIGNAL FIELD: Portion of the 802.11 HT PHY PPDU that contains “Rate” and “Duration”, part of the PLCP header.

Symbol: Typically refers to an OFDM symbol, which is a collection of sub-carriers (or tones)

4 Abbreviations and acronyms

Term	Description
ACK	Acknowledgement
AGC	Automatic Gain Control
AP	Access Point
BF-MIMO	Beamforming MIMO
CAP	Controlled Access Phase
CDD	Cyclic Delay Diversity
CRC	Cyclic Redundancy Check
CSI	Channel State Information
CSIT	Channel State Information at the Transmitter
CTS	Clear to Send
DLP	Direct Link Protocol
EPP	Extended PHY Protection
ERP	Extended Rate PHY
FCS	Frame Check Sequence
FPD	Following Packet Descriptor
HC	Hybrid Controller
HT	High Throughput
HT-LTF	High Throughput Long Training Field
HT-SIG	High Throughput Signal Field
HT-STF	High Throughput Short Training Field
ICB	Increase Channel Bandwidth MPDU
IE	Information Element
LAC	Link Adaptation Control
LLC	Logical Link Control
L-LTF	Legacy Long Training Field
L-SIG	Legacy Signal Field
L-STF	Legacy Short Training Field
MAC	Medium Access Controller
MCS	Modulation Coding Scheme – includes modulation order (BPSK, QPSK, 16-QAM, 64-QAM, 256-QAM) and FEC code rate (1/2, 2/3, 3/4, 7/8)

MFB	MCS Feedback
MIMO	Multiple input, multiple output (Both transmitter and receiver have multiple antennas for signaling over a point-to-point link)
MISO	Multiple input, single output (transmitter has multiple antennas but receiver has a single antenna)
MMP	MRA Multi-poll
MPDU	MAC protocol data unit
MRA	Multiple Receiver Aggregate – an aggregate that contains MPDUs for multiple receiver addresses.
MRC	Maximum Ratio Combining (a technique to maximize received SNR using antenna signal combining).
MRQ	MCS Request
MSDU	MAC service data unit
NAV	Network Allocation Vector (a MAC-level carrier-sense)
N _{RX}	Number of Receive Antennas
N _{SD}	Number of Data Subcarriers
N _{SS}	Number of Spatial Streams
N _{STS}	Number of Space-Time Streams (created after STBC encoding)
N _{TX}	Number of Transmit Antennas
OFDM	Orthogonal Frequency Division Multiplexing
PHY	Physical Layer
PLCP	PHY layer convergence protocol
PPDU	PHY protocol data unit
PSDU	PHY service data unit
Pure Mode	A mode of operation of a BSS in which there are no legacy devices
QAP	QoS access point
QoS	Quality of service
QSTA	QoS station
RAC	Royal Automobile Club
RDG	Reverse Direction Grant
RDR	Reverse Direction Request
RDTID	Reverse Direction Traffic Identifier
RPO	Response Period Offset
RR	Rate Recommendation

RSSI	Receive Signal Strength Indicator
RTS	Request to send
RX	Receiver
SAP	Service Access Point
SF	Signal Field
SIFS	Short inter-frame spacing
SIMO	Single input, multiple output (transmitter has a single antenna, receiver has multiple antennas)
SISO	Single input, single output (both transmitter and receiver have a single antenna)
SoP	Start of Packet (i.e. PPDU Packet)
SRA	Single Receiver Aggregate – an aggregate that contains MPDUs for a single receiver address.
STA	Station
SVD	Singular Value Decomposition: For an arbitrary matrix $A = USV^H$
TC	Traffic Category
TGe	802.11 Task Group e - Quality of Service
TGn	802.11 Task Group n - Enhancements for Higher Throughput
TRQ	Training Request
TS	Traffic Stream
TSID	Traffic Stream Identifier
TSPEC	Traffic specification
TX	Transmitter
TXOP	Transmission opportunity

1
2

5 Introduction

5.1 Purpose

This document defines proposed Enhancements for Higher Throughput within the scope of the Project Authorization Request (PAR) [3] formulated for IEEE 802.11 Task Group n.

5.2 General description of MAC enhancements

The proposed MAC enhancements assume a baseline specification defined by IEEE 802.11 standard [1] and its later amendments, including the draft IEEE 802.11e amendment [2]. The purpose of the enhancements is to significantly improve throughput, providing a maximum throughput of at least 100Mbps, as measured at the MAC data service access point (SAP).

The features supported by this TGn Sync MAC proposal are as follows:

- A Frame Aggregation format that allows aggregation of multiple Data and Control MPDUs in one PPDU. Note, an aggregate can also include a single management frame, in addition to multiple data and control frames per unicast receiver address. Aggregation is supported at the MSDU level and at the MPDU level.
- Aggregate frame exchange rules that control the exchange of multiple MPDUs per PPDU between an initiating STA and a responding STA.
- Multi receiver Multi-Poll (MMP) sequence rules that allow the exchange of multiple MPDUs between an AP and multiple responding STA and support enhanced power saving at the STA.
- A receiver assisted channel training protocol.
- A reverse direction data protocol that allows efficient channel access for single and multiple responders within a frame exchange sequence.
- Protection of the new frame exchange sequences may be provided through one of two mechanisms: a MAC-level mechanism based on NAV reservations, and a PHY-level mechanism using the legacy PLCP rate/length information.
- Mechanisms to manage coexistence of legacy and HT devices.
- Channel management and channel selection methods.

5.3 General description of PHY enhancements

With the aim to increase the maximum PHY layer data rate, we have introduced two primary techniques in our proposal:

-
- Transmission of Multiple Spatial Streams via Multiple Transmit Antennas. Our recommendation is to make 2 spatial streams mandatory, with the option to scale to 4 spatial streams.
 - Extended Bandwidth signaling. 20MHz channelization shall be mandatory worldwide. Our recommendation is to support 40MHz channelization in regulatory domains that will permit wider bandwidth operation
- We have also introduced several secondary techniques for increasing throughput. These include:
- Increasing the number of data tones to 52 in 20MHz.
 - A reduced guard interval of 400ns (i.e. half-GI), channel dispersion permitting (e.g. TGn channel model B). Support for half-GI is optional.
 - Higher channel coding rate of 5/6. Support for 5/6 is mandatory in 20MHz.
 - Optional support for 256-QAM in the Transmit Beamforming mode.
- Due to the susceptibility of a wireless link to multipath fading, especially in a MIMO channel, our proposal introduces three optional techniques for improving the robustness of the link between the transmitter and the receiver, with the aim to keep the client (station) configuration low-cost and low-power:
- Transmitter beamforming (TxBF).
 - STBC (Space-Time Block Coding)
 - Advanced channel coding. Our proposal includes LDPC as an option. LDPC codes exhibit a larger minimum free distance compared to the existing 802.11a convolutional code, and hence are able to better exploit the frequency and spatial diversity in the channel.
- Our proposal supports full backwards compatibility with existing 802.11a/b/g standards. Our preamble design support PHY layer interoperability with the OFDM preamble from 802.11a/g, while providing a robust mechanism for synchronization of the high throughput data.

6 Frame Formats

This clause specifies the format of new HT frames.

Reserved fields and subfields shall be transmitted as zeroes and shall be ignored by an HT receiver

6.1 MPDU Header

6.1.1 Frame Control Field

The Order field of the Frame Control field is defined as following:

Context	Description
non-QoS Data MPDU	As defined in 802.11
QoS data, BAR and BA	RDG/More PPDU as defined below

6.1.2 RDG / More PPDU Field

This meaning of this field depends upon the role of the device transmitting the frame as follows:

Role	Value	Description
Initiator	0	No reverse grant
"RDG Field"	1	A reverse grant is present, as defined by the Duration/ID field. The response PPDU(s) shall fit within the duration defined in the Duration/ID field of the MPDU carrying the RDG
Responder	0	The PPDU carrying the MPDU is the last transmission by the responder.
"More PPDU Field"	1	The PPDU carrying the MPDU is followed by another PPDU.

The "More PPDU Field" shall be set to the same value in all MPDUs of type QoS Data, BAR and BA within the same response aggregate.

6.2 Control frames

This section defines new control frame subtypes as listed below:

Control Frame Subtype	Name
LAC	Link adaptation control
MMP	Multiple receiver aggregate multi-poll
Calibration Training	Calibration Training frame

6.2.1 Link Adaptation Control (LAC) MPDU

6.2.1.1 Introduction

This MPDU supports control of MIMO training requests and exchange of link adaptation information. It may be sent by either initiator or recipient during an aggregation exchange. It may be sent by itself (in which case the response is another LAC frame, or aggregated in either direction).

There are a number of groups of fields (LAC elements), which perform specific purposes within the MPDU as described below:

Element Name	Purpose of item
RTS – Request to Send	Detects collisions at the receiver Tests state of NAV in the receiver Sets NAV reservation near Transmitter (LongNAV)
CTS – Clear-to-Send	Response to RTS indicates that the medium is clear
TRQ – MIMO training request	Request to train the channel Used for MIMO with implicit Feedback.
MRQ – MCS request	Request for MCS feedback
MFB – MCS Feedback	Closed loop channel adaptation feedback

Note, although described as "elements", the structure of the LAC MPDU containing these elements is fixed.

6.2.1.2 Format of LAC MPDU

This section defines the format of the LAC MPDU.

The LAC MPDU has a fixed structure. Fields that are not used are present, but reserved.

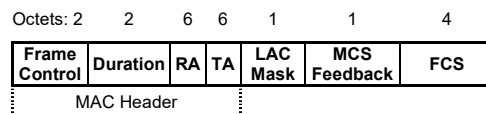


Figure 1 – LAC MPDU

Field	Size (bytes)	Purpose
Frame Control	2	Type is control, subtype is LAC
Duration	2	
Receiver Address	6	
Transmitter Address	6	
LAC Mask	1	A bitmask indicating which LAC elements are present in the packet.
MCS Feedback	1	Contains a recommended MCS value. Present when MFB is indicated, otherwise undefined.
FCS	4	

6.2.1.2.1 LAC Mask Field

This field indicates which logical elements are carried in the MPDU.

LAC Mask Field bit	Position	Description
RTS	B0	When set, indicates this is an RTS. The receiver should not generate any response if its NAV is non-zero.
CTS	B1	When set, indicates this is a CTS. It is present in a LAC transmitted in response to a LAC containing the RTS flag set to 1.
TRQ	B2	When set, indicates a request to train the channel. Used for MIMO with implicit Feedback.
MRQ	B3	When set, indicates a request for MCS feedback.
MFB	B4	When set, indicates an MFB training response is present as defined by the MCS Feedback field.

6.2.1.2.2 Format of MCS Feedback Field

This field contains an MCS value and a selection for the Short GI.

The least significant 7 bits carry the MCS TXVECTOR parameter.

The most significant bit (bit7) carries the SHORT-GI TXVECTOR parameter.

6.2.2 Multiple Receiver Aggregate Multi-Poll (MMP) MPDU

6.2.2.1 Introduction

The MMP frame is used to define multiple response periods, in combination with multiple-receiver aggregation.

The MMP frame may be transmitted in a separate PPDU, or may be aggregated with the first MRA of the MMP sequence. See section 7.1.4 (MMP exchange sequences).

6.2.2.2 Format of MMP MPDU

This section defines the format of the MMP MPDU.

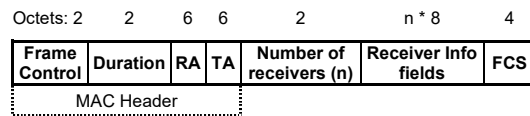


Figure 2 – MMP MPDU

Field	Size (bytes)	Purpose
Frame Control	2	Frame type is Control, subtype MRAD
Duration	2	
Receiver Address	6	The RA field is the broadcast group address.
Transmitter Address	6	The TA field is the address of the STA transmitting the MRA aggregate.
Number of receivers	2	The number of receivers (n) for which MPDUs are included inside the MRA aggregate.
Receiver Info fields	n * 8	n Receiver Info fields, one for each Receiver Address in the MRA aggregate.
FCS	4	

The order of the Receiver Info fields is equal to the order in which MPDUs for the corresponding receivers appear in the MRA aggregate.

Each receiver info field carries the following information

Subfield	Size	Purpose
AID	2 bytes	Contains an association identifier that identifies the STA addressed by this record
TID	4 bits	Defines the TID for transmissions by the STA
Reserved	4 bits	

Rx Offset	10 bits	Defines the start of the PPDU containing the downlink data. Specified in units of 4us relative to the end of the MMP PPDU. Reserved if Rx Duration is zero.
Rx Duration	10 bits	Locates the end of the downlink data ¹ relative to the Rx Offset, in units of 4 us. Contains zero if there is no downlink data for this AID.
Tx Offset	10 bits	Defines the time when transmissions by this STA may start, in units of 4us relative to the end of the MMP PPDU. Reserved if Tx Duration is zero.
Tx Duration	10 bits	Defines the limit of transmission duration, in units of 4us. Contains a zero if no transmission is scheduled.

6.2.3 Block Ack (BA) MPDU

This section defines a compressed variant of the 802.11e BA MPDU. The variant is distinguished by setting the "Compressed" field of the BA Control field to 1.

The compression is achieved by removing fragmentation from the Block Ack mechanism, which reduces the bitmap size to 1 bit per MSDU.

The use of this mechanism is negotiated when the BA agreement is created through the exchange of ADDBA frames, and is constant for a BA agreement throughout its lifetime. This means that a BA for a particular BA agreement is always the same size.

6.2.3.1 Format of BA MPDU

The frame format for the BA frame is defined as in Figure 3.

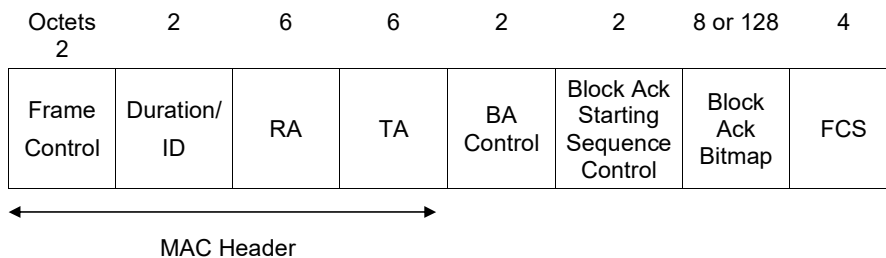


Figure 3 – Compressed BA MPDU

Only the BA control and Block Ack Bitmap fields are modified.

¹ Strictly: the end of the last symbol containing any data for this AID referenced to the start of the PPDU.

The BA Control Field is shown in Figure 4.

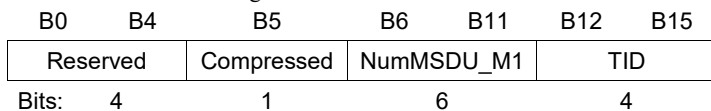


Figure 4 – BA Control field

The Compressed and NumMSDU_M1 are new fields.

The Compressed field selects between legacy 802.11e format and compressed format. When the Compressed field is set to 0, the BA is interpreted according to legacy 802.11e, with a 128-byte bitmap. When the Compressed field is set to 1, the BA is compressed, with an 8-byte bitmap.

The NumMSDU_M1 field defines the number of MSDUs that are acknowledged by the present bitmap, less one. For example, the NumMSDU_M1 field set as 0 indicates 1 MSDU is acknowledged by the bitmap and when it is 63, 64 MSDUs are acknowledged. The value of NumMSDU_M1 ranges from 0 to Buffer Size – 1, where Buffer Size is the ADDBA parameter that defines the BA window size.

The bitmap is interpreted according to the setting of the Compressed field, as defined in the following table.

Table 1 – Interpretation of the BA Bitmap

Compressed	NumMSDU_M1	Bitmap Length	Bitmap interpretation
0	0	128	Legacy 802.11e BA.
1	0 to 63	8	HT BA. Bit n acknowledges (if 1) or negatively acknowledges (if 0) an MSDU with Sequence Control = Block Ack Starting Sequence Control + 16*n. The first NumMSDU_M1 bits are valid; the remaining bits are ignored.

6.2.4 Calibration Training MPDU

The frame format of the Calibration Training MPDU is defined in Figure 5.

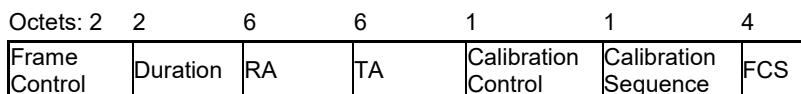


Figure 5 – Calibration Training MPDU

The Calibration Control field contains:

- Number of antennas at the initiating STA N_i (2 bits)

- Number of antennas at the responding STA N_r (2 bits)
- Position (2 bits). This field is set to '0' by the STA transmitting the first frame that initiates the calibration training frame exchange sequence. The field is incremented in subsequent Calibration Training frame transmissions in the calibration training frame exchange sequence.
- *Reserved* (2 bits)

The Calibration Sequence field is incremented at the transmission of the Calibration Training frame that initiates the calibration procedure. The remaining frames in the same calibration procedure use the same Calibration Sequence value.

The Calibration Training frame is carried in a PPDU with attributes defined according to the value of the position field.

Table 2 – PPDU attributes for Calibration Training MPDUs

Position Field	PPDU	TXVECTOR NLTF	TXVECTOR SOUNDING
0	Non-Aggregate		0
1	Non-Aggregate, Sounding	N_r	1
2	Non-Aggregate, Sounding	N_i	1

The Calibration Training frame shall be transmitted in a non-aggregate PPDU as part of the calibration training exchange defined in 8.3.

6.3 Management frame formats

6.3.1 HT Capabilities

Support for any optional features or behavior will be declared through a STA's capabilities or management elements.

Table 3 –HT Capabilities

Capability	Location Size and Encoding	Contents
HT Supported	B0 1 bit Set to 1 to indicate HT support, set to 0 otherwise.	Indicates that the device is an HT device, supporting all the mandatory features of this document. This capability is indicated by the presence of the HT capability element.
Supported Channel Width Set	B1 1 bit Set to 0 to indicate {20}, set to 1 to indicate {20,40}	Contains: {20} for a device only capable of 20MHz operation {20, 40} for a device capable of both 20MHz and 40MHz operation.
MMP Supported	B2 1 bit Set to 1 to indicate MMP support, set to 0 otherwise.	When transmitted by a STA, indicates it is able to interpret the MMP frame and respond to a poll through the MMP mechanism (see section 7.1.4). It also means that a STA is capable of receiving an MRA (see section 7.1.4). When transmitted by an AP, indicates that it is able to transmit MMP frames.
Advanced Coding Capability	B3 1 bit Set to 1 to indicate support for Advanced Coding. Set to 0 otherwise.	Advanced Coding Capability Indicates support for advanced coding. This field has the same format as the advanced coding field defined in section 10.1.1.8, where a bit set as one indicates that that coding type is supported.
Short GI Supported	B4 1 bit Set to 1 to indicate support for Short GI as a receiver, set to 0 otherwise	Indicates that the STA can transmit and receive PPDU's using the SHORT GI Feature.
Calibration Supported	B5 1 bit Set to 1 to indicate support for calibration exchanges as a responder, set to 0	Indicates that the STA can participate in the calibration exchange defined in 8.3.

Capability	Location Size and Encoding	Contents										
	otherwise											
Number of Rx Antennas	B6-7 2 bits. Contains number of antennas less one	Indicates the number of Rx Antennas										
Maximum Rx PSDU Length	B8-15 8 bits Integer in range 15-18	Indicates the maximum PSDU size that can be received by the STA. See section 7.5										
Supported MCS class	B16-31 16 bits Used as follows: <table border="1"><thead><tr><th>Bits</th><th>Capability</th></tr></thead><tbody><tr><td>16-19</td><td>Tx 20MHz</td></tr><tr><td>20-23</td><td>Rx 20MHz</td></tr><tr><td>24-27</td><td>Tx 40MHz</td></tr><tr><td>28-31</td><td>Rx 40MHz</td></tr></tbody></table> If the supported channel bandwidth is only 20MHz, B24-B31 are reserved.	Bits	Capability	16-19	Tx 20MHz	20-23	Rx 20MHz	24-27	Tx 40MHz	28-31	Rx 40MHz	Defines the MCS capability supported by a STA. MCS capability is specified independently for 20 MHz and 40 MHz. See section 11.1.1.8.1 ??update for a list of MCS capability class.
Bits	Capability											
16-19	Tx 20MHz											
20-23	Rx 20MHz											
24-27	Tx 40MHz											
28-31	Rx 40MHz											

6.3.1.1 HT Capability element

The HT Capability element contains a number of subfields that are used to advertise optional HT capabilities at an HT device. The HT Capability element is present in beacons, association and re-association request frames and in probe response frames. The presence of the HT Capability element indicates that the device is an HT device. The HT Capability element is defined in Figure 6.

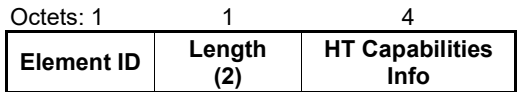


Figure 6 – HT Capability element format

6.3.2 Additional HT Information Elements

The AP will signal information in new information elements to manage the BSS. This information is defined in the table below.

6.3.2.1 HT Management Element

The AP will signal information in the HT Management Element defined here to manage the BSS, as shown in Figure 8. This element shall be present in all beacons and probe responses transmitted by a HT AP and by a HT STA in IBSS mode.

Octets: 1	1	6
Element ID	Length (6)	HT Management Element

Figure 7 – HT Management Element Format

This information subfields in the HT Management Element field are defined in the table below.

Table 4 – HT Management Element Subfields

Name	Description and Encoding
Legacy Protection	Indicates that legacy protection is required B0 1 bit Set 1 to indicate legacy protection, set to 0 otherwise
HT20 Protection	Indicates that HT20 protection is required B1 1 bit Set to 1 to indicate HT20 Protection, set to 0 otherwise
Extension Channel Control	B2-3 2 bits Values: 0-3 0 indicates {20, 40} 20MHz transmissions only are permitted Set to 0 1 indicates {20} that both 20MHz and 40MHz transmissions are permitted 2 indicates the 20MHz phase of 20MHz-base Managed operation as defined in section 8.1.2.3 3 indicates the 40MHz phase of 20MHz-base Managed operation as defined in section 8.1.2.3
Extension Channel Offset	B3 1 bit B4-5 Integer: 2 bits Values: 0, -1, 1 indicate offset of the extension channel from the Extension Channel Offset information element control channel. Value of 0 indicates no extension channel is present.
Control Channel	Channel number of the control 20MHz channel B6-15 Integer: 10 bits
Extension Channel Access Timeout	B16-23 8 bits Integer

	It specifies a time limit (in TU) after which the AP gives up the transition to 40 MHz and the 40 MHz capable HT STA switches back to 20 MHz if it has not received CTS-to-self or Beacon on the extension channel. Value = 0 otherwise
Basic MCS Capability	B24-31 8 bits Indicates the required MCS capabilities to become a member of the BSS. B24-27 indicate the required level of receive operation in 20MHz. B28-31 indicate the required level of receive operation in 40MHz. B28-31 are reserved if the Extension Channel Control is 0
HT Basic Rate	B32-47 16 bits Indicates the maximum rate that can be used to transmit protection and broadcast frames using a HT PPDU format

6.3.2.2 TSF Synchronization Precision Capability Element

The TSF synchronization precision capability transmitted by an AP indicates the precision of its beacon transmission start time at the output of AP to the media relative to TSF timer updates. This value represents the amount of jitter present in the timestamp in the beacon relative to TSF timer update timing. It includes all jitter introduced in the process of beacon generation through both MAC and PHY.

This element is present in Association, Reassociation and Probe Response frames.

This information is used to inform other stations of the ability of the AP to support synchronization within a communicated precision.

The TSF Synchronization Precision Capability Element is given in Figure 8.

Octets: 1	1	1
Element ID	Length (2)	SyncPrecision

Figure 8 – TSF Synchronization Precision Capability Element

The SyncPrecision field contains a non-negative integer in the range 0-20 representation that indicates the amount of synchronization of TSF at the output of AP is $2^{(-\text{SyncPrecision})}$ in units of μs .

6.3.3 Management Action Frames

These frames are defined to be action frames using the 802.11e Action frame format. They share a common category code "HT".

The frames using the "HT" category code are defined in Figure 9.

Action Code	Meaning
1	Calibration Measurement
2	Calibration Correction

Figure 9 – Action codes for the HT action category

6.3.3.1 Calibration Measurement Action Frame

Calibration Measurement frame is a management action frame of category Calibration. It contains the following fields.

Order	Information	Size
1	Calibration Control	1
2	Calibration Sequence	1
3	MCMR Segment Sequence	1
4	MIMO Channel Measurement Report	$3 \times N_s \times N_i \times N_r$
Where:		
N_s = Number of subcarriers in the Calibration Training symbols N_i = Number of antennas at the STA that transmitted the Calibration Request N_r = Number of antennas at the STA that is transmitting the Calibration Response		

All messages in the same calibration procedure use the same Calibration Sequence value.

The Calibration Control field (1 octet) consists of:

- Number of antennas at the initiating STA N_i (2 bits)
- Number of antennas at the responding STA N_r (2 bits)
- Calibration Complete (1 bit). The Calibration Complete bit is set to '1' if the STA transmitting the Calibration Measurement frame declares the calibration procedure complete without requiring the other STA to transmit a Calibration Correction Vector frame.
- Reserved (3 bits)

The MCMR Segment Sequence (1 octet) contains the segment sequence number when the MIMO Channel Measurement Report has been segmented. The MCMR Segment Sequence of the first segment is 0. The complete MIMO Channel Measurement Report contains $N_s \times N_i \times N_r$ complex coefficients.

Each complex coefficient (3 octets) is represented by its 12-bit signed real and 12-bit signed imaginary parts. Hence the total length of the complete MIMO Channel Measurement Report is $3 \times N_s \times N_i \times N_r$ octets. The order of channel coefficients is as follows:

40 MHz:

For each subcarrier in the following order: (-58, ..., -2, 2, ..., +58), include

```
{
    For each of  $N_i$  antennas at the initiating STA in order: (1, ...,  $N_i$ )
    {
        Include  $N_r$  complex coefficients one for each antenna at the receiving STA in
        order: (1, ...,  $N_r$ )
    }
}
```

20 MHz:

For each subcarrier in the following order: (-28, ..., -1, 1, ..., +28), include

```
{
    For each of  $N_i$  antennas at the initiating STA in order: (1, ...,  $N_i$ )
    {
        Include  $N_r$  complex coefficients one for each antenna at the receiving STA in
        order: (1, ...,  $N_r$ )
    }
}
```

The complete MIMO Channel Measurement Report may need to be transmitted using more than one MAC frame. In the mandatory configuration with $N_s = 114$, $N_i = 2$, $N_r = 2$, there will be 1368 octets (456 coefficients) in a single MIMO Channel Measurement Report element. The maximum length of the MIMO Channel Measurement Report field is 5472 octets (1824 coefficients) for the case with $N_s = 114$, $N_i = 4$, and $N_r = 4$. If the MIMO Channel Measurement Report is longer than 1368 octets, the first 1368 octets are included in the first frame (MCMR Segment Sequence = 0) and the remaining octets are included in subsequent frames (MCMR Segment Sequence = 1, 2, etc.).

6.3.3.2 Calibration Correction Action Frame

Calibration Correction frame is a management action frame of category Calibration Correction. It contains the following fields.

Order	Information	Size
1	Calibration Control	1
2	Calibration Sequence	1
3	MIMO Correction Vector	$3 \times N_s \times N_r$
Where:		
N_s = Number of subcarriers in the Calibration Training symbols N_r = Number of antennas at the STA that transmitted the Calibration		

Response

All frames in the same calibration procedure use the same Calibration Sequence value.

The Calibration Control field (1 octet) consists of:

- Number of antennas at the initiating STA N_i (2 bits)
- Number of antennas at the responding STA N_r (2 bits)
- Reserved (4 bits)

The MIMO Correction Vector contains $N_s \times N_r$ complex coefficients.

Each complex coefficient (3 octets) is represented by its 12-bit signed real and 12-bit signed imaginary parts. Hence the total length of the MIMO Correction Vector field is $3 \times N_s \times N_r$ octets. The order of correction vector coefficients is as follows:

40 MHz:

For each subcarrier in the following order: (-58, ..., -2, 2, ..., +58), include

{
 Include N_r complex coefficients one for each antenna at the receiving STA in order: (1, ..., N_r)
}

20 MHz:

For each subcarrier in the following order: (-28, ..., -1, 1, ..., +28), include

{
 Include N_r complex coefficients one for each antenna at the receiving STA in order: (1, ..., N_r)
}

The maximum length of the Correction Vector field corresponds to $N_s = 114$, $N_r = 4$ is 1368 octets.

6.3.4 Block Ack Parameter Set field

This section defines changes to the 802.11e Block Ack Parameter set field of the ADDBA frame.

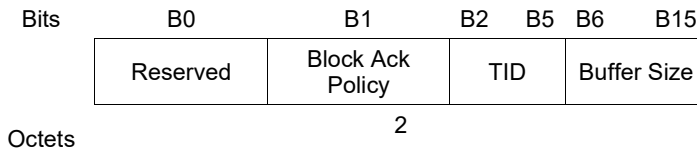


Figure 10 - Block Ack Parameter Set fixed field

The Block Ack Policy field is defined as Delayed Block Ack or Immediate Block Ack in 802.11e. The same field is redefined for HT stations, whereby the value of 0 corresponds to HT Partial State Block Ack, and the value of 1 corresponds to HT Immediate Block Ack. The details

of these enhanced BA mechanisms are described in section 2.4. An HT STA shall support the HT Partial State BA at a minimum

The Buffer Size field contains the number of buffers at the receiver. Its interpretation depends on the type of BA, as specified in the following table.

Table 5 - Interpretation of the Buffer Size parameter

Block Ack Type	Buffer Size interpretation
Compressed	Buffer size contains the maximum number of MSDUs that can be sent within the BA window. Maximum value is 64
802.11e	Buffer size contains the maximum number of MPDUs that can be sent within the BA window. Maximum value is 1024 (<i>i.e.</i> 64 x 16)

In an ADDBA request frame, the Buffer Size subfield is advisory and the recipient should select a value equal to or smaller than the initial value.

6.4 A-MPDU and A-MSDU aggregation formats

6.4.1 Introduction to Aggregation (Informative)

There are two types of aggregation defined in this specification: A-MSDU aggregation and A-MPDU aggregation.

A-MSDU aggregation joins together multiple MSDUs and creates a single larger MSDU that is transported in Data MPDUs.

A-MPDU aggregation joins multiple MPDUs together and transports them in a single PSDU.

Note, the term "aggregate" used elsewhere in this document refers to A-MPDU aggregation, unless specifically referring to A-MSDU aggregation.

The MAC interprets the PSDU as a single MPDU, or as an A-MPDU according to the A-MPDU TXVECTOR/RXVECTOR parameter, which is robustly transported in the PLCP header.

The Duration fields in the MAC Headers of all MPDUs in an aggregate carry the same value.

6.4.2 Aggregated MPDU format (A-MPDU)

An A-MPDU consists of a number of MPDU delimiters each followed by an MPDU. Except when it is the last MPDU, padding octets are appended (if needed) to make each section a multiple of 4 octets in length.

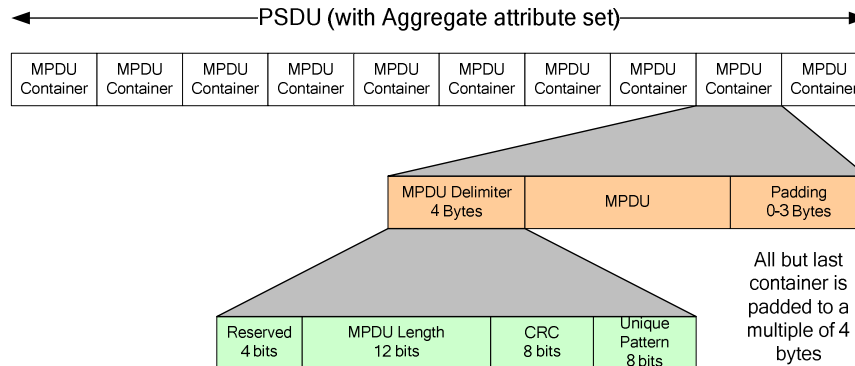


Figure 11 – A-MPDU format

The MPDU delimiter is 4 octets in length and contains the fields defined below:

Table 6 – MPDU delimiter Fields

MPDU delimiter Field	Size (bits)	Description
Reserved	4	-
MPDU length	12	Length of the MPDU in octets
CRC	8	8-bit CRC of the preceding 16-bits. As defined in IEEE 802.11 section 14.3.2.2.3
Unique pattern	8	Unique pattern that may be used to detect an MPDU delimiter when scanning for a delimiter. The unique pattern is set to the ASCII value for character 'N'.

The purpose of the MPDU delimiter is to robustly delimit the MPDUs within the aggregate. Robust in this case means that the structure of the aggregate can usually be recovered when one or more MPDU delimiters are received with errors. Individual delimiters have the same BER as the surrounding MPDUs, and so can be lost.

Note, a delimiter with MPDU length zero is valid. This can be used to introduce padding between MPDUs, or at the end of the A-MPDU.

6.4.3 Single receiver frame aggregation format

An A-MPDU aggregate is a sequence of MPDUs carried in a single PPDU with the TXVECTOR A-MPDU field set to 1.

In a single-receiver aggregate, all MPDUs are addressed to the same receiver address.

The aggregate contains MPDUs in the order defined below.

Table 7 Single Receiver Aggregation MPDUs

MPDU	Multiplicity	Description
ACK	At most one	Contains an acknowledgement of at most one MPDU in the previous aggregate that required immediate acknowledgement.
BA	At most one per Block ACK agreement in the appropriate direction	Block ACK MPDUs
QoS Data	No limit, except as constrained by Block ACK protocol and TXOP duration	Data MPDUs sent under Block-ACK policy.
LAC	At most one	Link adaptation control Used when it is necessary to include a logical element as described in section 7.1.5. This MPDU may only occur anywhere within the aggregate after any response MPDUs (Ack, BA) and before any MPDUs requiring an immediate response.
BAR	At most one per Block ACK agreement.	Block ACK Requests
Any MPDU requiring an immediate response	At most one	At most one MPDU for which an Ack MPDU response may be transmitted. This includes non-QoS Data MPDU and Management MPDU. BAR sent under Partial State Block Ack Policy may also generate an Ack MPDU response, but it is allowed to send multiple BARs as they will generate a single Ack MPDU.

6.4.4 Multiple receiver frame aggregation format

A multiple-receiver aggregate (MRA) contains MPDUs that are addressed to multiple receivers.

An MRA may only be transmitted during an MMP sequence (as defined in section 7.1.4). A STA may only be addressed in an MRA if it has declared support for the MMP capability. Broadcast/Multicast frames shall not be transmitted in an MRA.

In the MRA, frames for each receiver address are grouped together. Each group shall contain the same MPDUs as a Single Receiver Aggregate (see section 6.4.3), addressed to the same receiver, in the order defined in Table 7. The order of (groups of) Data MPDUs for different receiver addresses is equal to the order of the matching Receiver Info fields in the previous MMP MPDU.

The RDG field shall be set to 0 in all MPDUs within an MRA.²

Data MPDUs can come from multiple TCs, provided that they comply with the TC policy of the current TXOP.

6.4.5 Aggregated MSDU Format (A-MSDU)

This section describes the format of Aggregated MSDU (A-MSDU). The purpose of the A-MSDU is to allow multiple MSDUs being sent to the same receiver to be aggregated and sent in a single MPDU, which improves the efficiency of the MAC layer, particularly when there are many small MSDUs such as TCP acknowledgements. Support for A-MSDU is mandatory at the receiver. However, the transmitter is free to use A-MSDU or not based on information such as traffic characteristics and link conditions. The maximum length of an A-MSDU is 3800 bytes.³

Figure 12: A-MSDU Structure shows the structure of a Data MPDU containing an A-MSDU, which is a sequence of n MSDU sub-frames. Each sub-frame consists of a sub-frame header followed by an MSDU and 0-3 bytes of padding. A sub-frame (except the last) is padded so that its length is a multiple of 4 bytes. The last sub-frame has no padding.

The sub-frame header contains three fields: Destination Address (DA), Source Address (SA), and Length.⁴ The DA and SA fields are interpreted as described in Table 8 below. The length field contains the length in bytes of the MSDU.

² Any uplink direction data transmission during an MMP sequence is scheduled through the MMP.

³ This figure is chosen so that the length of an MPDU containing an (unfragmented) A-MSDU does not exceed 3839 bytes. The figure of 3839 is chosen so that the maximum length MPDU containing an A-MSDU is 256B shorter than a common physical memory page size of 4KB, thereby allowing room for status and control information to be stored with the MPDU without forcing the use of multiple physical pages.

⁴ Note, these fields are arranged in the same order as the 802.3 frame format.

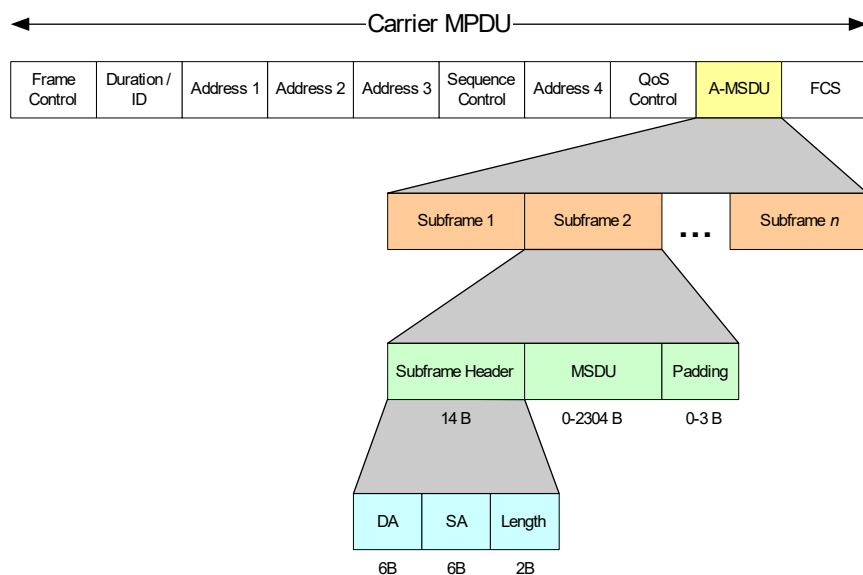


Figure 12: A-MSDU Structure

The MPDU containing the A-MSDU is one of the QoS data subtypes. The presence of the A-MSDU is signaled by setting bit 7 of the QoS control field to a 1.

The DA and SA are passed between the MAC and its service client in the MAC service primitives. The mapping of DA, SA to the addresses in the MPDU header is described by the following tables. It is possible to have different DA and SA in the same A-MSDU as long as they all map to the same receiver address.

1

Table 8 – Address field contents

To DS	From DS	Address 1	Address 2	Address 3	Address 4	DA	SA
0	0	DA	SA	BSSID	X	-	-
0	1	DA	BSSID	-	X	-	SA
1	0	BSSID	SA	-	X	DA	-
1	1	RA	TA	-	-	DA	SA

Notes:

X = not present

- = reserved

2

3

4

7 MAC sublayer functional description

7.1 Aggregation Exchange Sequences and related rules

7.1.1 Aggregation Exchanges

A STA that owns the TXOP may start an exchange of PPDU's. This STA is called the initiator.

The initiator STA may transmit PPDU's and obtain response PPDU's from one or more STA during the exchange. These STA are called responders.

A response may contain either:

- A singleton response PPDU containing one or more of the following response MPDU's: CTS, LAC, BA and Ack
- A response burst consisting of one or more PPDU's that may contain data as well as response MPDU's

In the case of a singleton response PPDU, all relevant MPDU's in the PPDU shall have the "More PPDU" field set to 0. In the case of a response burst, the last response PPDU shall have the "More PPDU" field set to 0 in all MPDU's of type: BA, BAR, QoS Data.

A response may be transmitted as defined in Table 9.

Table 9 – Response Generation

Transmission by initiator	Response
An aggregate or non-aggregate PPDU containing one or more unicast frames addressed to the receiver with the RDG field set to 1.	A response burst starting a SIFS after the end of the initiator's transmission, and lasting no longer than the RDG duration (less a SIFS)
An aggregate or non-aggregate containing one or more frames addressed to the receiver that require a response, not transmitted as part of an MMP exchange sequence and not containing any frame with the RDG field set to 1 (i.e., not a reverse direction grant).	A singleton response PPDU containing only response MPDU's transmitted a SIFS after the end of the initiator's transmission
An MMP frame containing an entry for the responder with non-zero tx-duration	A response burst at the specified tx offset relative to the end of the MMP packet lasting no longer than the tx duration specified in the MMP packet.

The initiator shall ensure that its PPDU transmission and any responses fit entirely within the current TXOP.

7.1.2 Bi-Directional Data Exchange Rules

Transmission of an MPDU by an initiator with the RDG flag set to 1 (either transmitted by itself, or as part of an aggregation) indicates that the period of time defined by the MPDU's Duration field is available for a response burst. The initiator is free to grant any RDG it wishes (compliant with the TXOP rules).

The responder may only transmit Data MPDUs of the same AC as the MPDU carrying the RDG. The responder may only transmit MPDUs addressed to the Initiator, i.e., RA=Initiator. The transmitted response burst shall last no longer than the granted duration.

After transmitting a PPDU containing a reverse direction grant, the initiator may transmit its next PPDU a SIFS after receiving a response PPDU with the "More PPDU" flag set to 0. It may transmit its next PPDU when the medium is sensed idle for PIFS.

7.1.3 Protection mechanisms

7.1.3.1 LongNAV protection

When a STA has a TXOP, it may set a long NAV to protect multiple PPDUs using a single protection MAC layer protection exchange, e.g., RTS/CTS.

LongNAV protection is defined as selecting a duration value, limited by the remaining duration in the current TXOP and setting the NAV to this value using one of the MAC layer protection techniques.

In the case that a STA gains access to the channel using EDCA and uses LongNAV to protect a duration value, and then runs out of MPDUs to transmit, the STA may transmit a CF-End provided that the remaining duration is long enough to transmit this MPDU.

This shall be interpreted by HT STAs and is interpreted by legacy STAs as a NAV reset – i.e. they reset their NAV timer to zero at the end of the PPDU containing this MPDU.

7.1.3.2 Extended PHY Protection

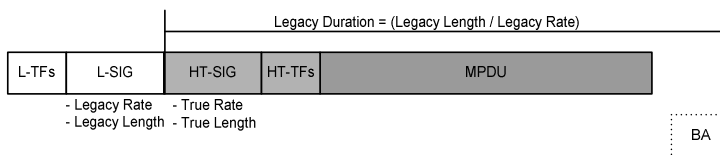


Figure 13: Extended PHY protection

A STA may use Extended PHY Protection (EPP) to provide protection of an exchange of packets, by utilizing the Legacy SIGNAL (L-SIG) portion of an HT PPDU. With EPP, the NAV Duration value is virtually carried in the Length and Rate Fields of the L-SIG.

EPP provides robust protection towards third party HT nodes along with legacy nodes with an HT PPDU, enabling protection packets to be sent in optimized MIMO PPDU. EPP is also effective in providing protection towards 20MHz-only capable STAs because the L-SIG portion of a 40MHz PPDU is decodeable in both halves of the 40MHz channel.

When EPP is in operation, the Length and Rate Fields of the L-SIG is set so that the end point of Legacy Duration = (Legacy Length / Legacy Rate) is equivalent to the intended NAV Duration⁵.

A legacy node that decodes these two fields will continue reception for (Legacy Length / Legacy Rate) time, preventing it to start transmission during this period.

An HT node that receives a PPDU examines the Rate and Length fields of the L-SIG and HT-SIG, from which it calculates Legacy and HT Durations. It determines that EPP is in operation if the Legacy Duration is longer than the HT Duration. When EPP is in operation, it shall set its NAV to the value of (Legacy Duration - HT Duration) ⁵ at the end of the received PPDU.

7.1.3.2.1 Extended PHY Protection with RTS/CTS

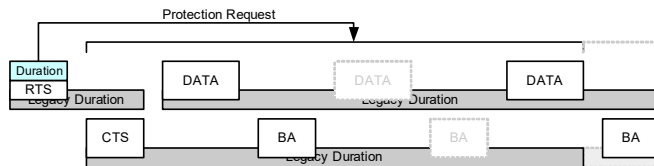


Figure 14: Extended PHY protection with RTS/CTS

A STA may use EPP to protect an exchange sequence to a single responder where an RTS/CTS handshake is necessary.

The EPP rules here are described in terms of an initial RTS/CTS exchange for convenience. The same rules shall be applied to any initial packet exchange, including a LAC/LAC exchange.

Extended PHY Protection with RTS/CTS - Rules at the Initiator

When the initiator intends to use EPP it may start a packet exchange with an RTS/CTS (or LAC/LAC equivalent) handshake. It shall set the Legacy Duration of the RTS PPDU so that it protects the expected response, the CTS.

In the RTS MPDU, the initiator shall notify the responder of the Protection Request Duration⁵, which the responder will use to set the Legacy Duration of the CTS. The Protection Request shall be carried in the Duration Field of the MAC Header in the RTS MPDU. The duration of the Protection Request shall be set to at least one response frame (CTS), plus SIFS, plus one DATA PPDU, and may be extended to protect multiple DATA/ACK exchanges.

⁵ (EIFS – DIFS) adjustment described in section 7.1.3.2.3 should be made

1 Upon reception of a CTS addressed to itself, the initiator shall start transmission of DATA
2 PPDUs. The Legacy Duration of the first DATA PPDU from the initiator shall point to the end
3 point of the CTS PPDU or may be set to a certain time beyond this end point. The duration of
4 this extension of Legacy Duration at the initiator shall be the time equivalent to SIFS plus the
5 duration of the expected final response from the responder.

6 When this extension of Legacy Duration is used, the initiator may choose to extend the EPP
7 period by sending an RTS MPDU within the already established EPP period. The Protection
8 Request Duration carried in the MAC Duration field of the RTS MPDU shall be set to the
9 amount of extension to the EPP period.

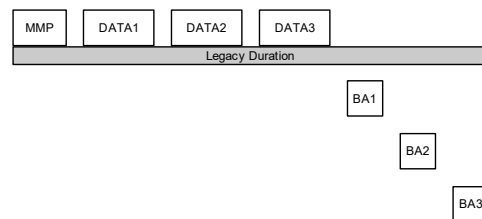
10 After a STA transmits a PPDU using EPP it shall set the Legacy Duration value to the end of the
11 EPP period on all the subsequent PPDU it transmits. The initiator shall wait until the end of the
12 current EPP period before transmitting a PPDU that establishes a new EPP period⁶.

16 Extended PHY Protection with RTS/CTS - Rules at the Responder

17 The responder, on receiving a RTS MPDU addressed to itself with EPP in operation, shall
18 generate a response PPDU with the L-SIG set to duration equal to the Protection Request
19 Duration.

21 After a STA transmits a PPDU using EPP it shall set the Legacy Duration value to the end of the
22 EPP period on all the subsequent PPDU it transmits. The initiator shall wait until the end of the
23 current EPP period before transmitting a PPDU that establishes a new EPP period⁶.

26 7.1.3.2.2 Single Ended EPP



28 **Figure 15: Extended PHY protection for an MMP sequence**

30 STA may use Single Ended EPP to protect an exchange sequence where RTS/CTS protection is
31 not necessary. This is especially effective in an MMP sequence where responses are expected
32 from multiple responders.

33 The initiator should set the Legacy Duration of the initial PPDU, so that it protects to the end of
34 the last response⁵. In case of a MMP sequence, the Legacy Duration of the MMP PPDU shall
35 protect up to the end of the scheduled response.

⁶ Because the L-SIG cannot be decoded by legacy while an EPP is active

1 7.1.3.2.3 EIFS Rules for EPP

2 The EPP periods shall be set (EIFS- DIFS) shorter than the actual duration required for NAV
3 protection. This is to avoid the unfairness towards legacy devices which will defer for EIFS
4 upon reception of a PPDU using EPP, which will cause a CRC error. HT nodes shall add (EIFS-
5 DIFS) to the EPP period when setting the NAV value set by a PPDU that uses EPP.

6 Upon sending a Protection Request in an RTS packet, it shall be the responsibility of the initiator
7 to make the (EIFS- DIFS) adjustment in the request, so that the responder can simply set its
8 Legacy Duration exactly as indicated in the Protection Request.

9 7.1.3.3 HT Device NAV and EIFS Rules

10 An HT device that receives a PPDU examines the legacy and HT rate and length fields from
11 which it calculates legacy and HT durations.

12 It determines that EPPEPP is in operation if the legacy duration is not equal to the HT duration.

13 If EPPEPP is in operation, it shall set its NAV to the value of legacy duration + (EIFS – DIFS) –
14 HT duration at the end of the received PPDU.

15
16 The following rule defines EIFS selection for an HT STA:

17 An HT STA that receives an MPDU with a bad CRC shall only use EIFS if its NAV is zero at
18 the start of the PPDU containing the MPDU. The condition is never true during an aggregate
19 exchange, but is true for isolated Data/ACK.

20 7.1.4 MMP Sequences

21 7.1.4.1 Introduction (Informative)

22 The MMP sequence is provided in response to two classes of comments on an earlier version of
23 this proposal. One comment regarded the complexity of the response generation using the
24 "reverse direction offset", which was mandatory in all STA, but there primarily to serve VoIP
25 and similar applications. The second regarded the need to more effectively support power-
26 saving in VoIP STA.

27
28 The MMP sequence addresses these requirements. The ability to participate in an MMP sequence
29 is optional, but all STA are able to decode at least the MMP header.. The MMP frame contains
30 addressing and timing information that allows a VoIP client to spend the minimum time awake
31 during the MMP sequence. 3rd party STA, not participating in the sequence, or supporting the
32 mechanism, can sleep through the entire sequence.

33
34 The existing 802.11e TSPEC mechanism is used to negotiate the creation of a periodic TSPEC.
35 It is an option of the AP whether and how to group service intervals of STA into MMP
36 sequences. It may use the MMP capability to determine that it can group STA together to
37 service the TSPEC as part of an MMP sequence.

38 7.1.4.2 Definitions

39 An MMP sequence starts with the transmission of an unaggregated MMP frame, and ends when
40 the last scheduled response contained in the MMP ends.

41 7.1.4.3 Rules at the AP

42 An AP shall only include a STA in an MMP if that STA declares support for MMP.

1
2 If the AP has grouped multiple STA to service under the MMP sequence, it shall transmit an
3 unaggregated MMP frame at the start of the service interval containing a record for each STA
4 that is to be serviced during the current service interval.
5
6 The MMP shall only contain records for STA that have declared support for MMP. The MMP
7 shall contain at most one record per AID/TID combination.
8
9 During an MMP sequence, the AP shall only transmit frames addressed to STA identified in the
10 MMP frame according to the schedule defined in the MMP frame.
11
12 The AP shall ensure that the first response period shall start no less than a SIFS after the end of
13 the MMP PPDU. Typically the initiator will arrange that response periods are separated by
14 SIFS, but there is no normative requirement for this to be the case.
15

16 **7.1.4.4 Rules at the STA**

17 A STA receiving an MMP shall be enabled to receive during its indicated Rx period, and may
18 transmit only during its indicated Tx period.
19
20 The STA shall only transmit frames for RA = AP.
21
22 If it transmitted any frames for which an immediate response is required, it shall wake to receive
23 responses at the end of the current MMP exchange.

24 **7.1.4.5 Protection Rules for MMP**

25 An MMP sequence may be protected using either LongNAV or EPP.
26
27 In the LongNAV case the NAV of all devices that can hear the initiator has already been set by
28 transmission of a previous MPDU, such as a CTS-to-self. In this case, the PPDU within the
29 MMP sequence should not use EPP because it limits the ability of the initiator to recover unused
30 RDG duration at the end of the response period.
31
32 The EPP case is applicable when there is no a-priori NAV setting. In this case the AP protects
33 the duration of the entire sequence as shown in section 7.1.3.2.2.
34
35 In the case of LongNAV protection, the initiator may continue with a transmission a SIFS after
36 the actual end of the last response PPDU. In the case of EPP, the initiator may continue its
37 transmission a SIFS after the end of the last response period, regardless of the actual length of
38 the response.
39

40 **7.1.4.6 Power-saving at the receiver of an MMP frame (informative)**

41 Once it has decoded the MMP frame at the start of the service interval, the STA knows when it
42 needs to be able to receive and when it can transmit. This may enable it to reduce power during
43 some or all of the 3rd-party downlink and uplink.
44

The downlink may be contained in one or more PPDU. The STA is given the start of the PPDU containing its downlink. The STA may also determine the starting offset of the data addressed to it relative to the start of the PPDU using the Rx Duration of the previous record in the MMP with a matching Rx Offset.

After acquisition, if the STA may be able to save power by disabling some of its receive mechanism, it can do so up to the first symbol containing its downlink data (MPDU). From that point, it decodes the data and scans for a valid MPDU delimiter. After it has received the indicated number of symbols of data defined in its receiver info record, it may sleep.

It also wakes to transmit at the time indicated in its receiver info field.

If it transmitted any frames requiring an immediate response, it shall wake at the end of the current MMP exchange to receive any responses.

7.1.4.7 Power-saving at the 3rd-party receiver of an MMP frame (informative)

An HT STA that receives an MMP may sleep through the remaining duration of the MMP sequence on the following conditions:

- It does not support MMP
- It does support MMP, and the MMP does not contain its AID

7.1.5 MAC support for closed loop modes

7.1.5.1 Closed-loop MCS training

Support for closed-loop MCS adaptation is provided by the exchange of MRQ (MCS Request) and MFB (MCS Feedback) elements carried in LAC control frames.

An MCS Request may be included in any LAC.

A STA receiving an MFB should use the information contained in it to adapt its transmission parameters.

A responder device that receives an unaggregated LAC shall respond with a LAC after a SIFS (assuming that the embedded RTS/CTS protocol (i.e., NAV setting) does not prevent such a response).

Assuming that the first LAC ("LAC1") transmitted by the initiator contains an MRQ, the second ("LAC2") transmitted by the responder may contain an MFB if the results are available quickly enough. Alternatively the responder may include a LAC ("LAC3") in a response aggregate at any time later once the results are available. In this case LAC2 does not contain an MFB element (indicating that no response is available yet), but LAC3 does.

When transmitted in an aggregate, a LAC frame only generates a response when the response contains at least one of the LAC elements. There is no need to acknowledge receipt of an aggregated LAC. This means that in the example above, if the MFB is not available immediately, LAC2 need not be included in the aggregate.

The MFB response is sent when it is available. That means that a device that can evaluate the MFB quickly may send it in the following PPDU. Other devices that evaluate it more slowly may send it in a later PPDU of the same sequence, or in a later sequence.

An STA sending an MRQ in a HT format PPDU shall set TXVECTOR SOUNDING to 1. If the transmission of segmented HT-LTFs is supported, it is also recommended that TXVECTOR NLTF be greater than the minimum value required for the current MCS, subject to a maximum value equal to the number of transmit antennas or 4, whichever is lower. The transmission of these additional HT-LTFs when sending an MRQ can aid MCS selection by the responder.

7.1.5.2 Closed-loop MIMO training

Support for closed-loop MIMO adaptation is provided by the exchange of a TRQ (MIMO Training Request) element carried in LAC control frames and an HT sounding PPDU.

A TRQ can be included in any LAC (except a legacy unaggregated LAC). Its purpose is to request the peer STA to return an HT sounding PPDU that allows the requesting STA to use better parameters for subsequent transmissions to the peer STA.

Use of Closed-loop MIMO training is completely optional. A STA that does not support closed-loop MIMO will never send an LAC with the TRQ flag set. A STA that receives a TRQ does not have to send a sounding PPDU in response.

A STA sending a sounding PPDU in response to a TRQ shall set TXVECTOR SOUNDING to 1. If the transmission of segmented HT-LTFs is supported, it is also recommended that TXVECTOR NLTF be greater than the minimum value required for the current MCS, subject to a maximum value equal to the number of transmit antennas or 4, whichever is lower. The transmission of these additional HT-LTFs when sending a TRQ can increase the performance of beamformed transmissions.

7.2 MCS selection rules

7.2.1 MAC Protection Frames – basic rate and PPDU type

Any frame that is used to set or reset the NAV shall be transmitted using a rate and PPDU format as defined here.

When legacy devices are present, only rates in the legacy basic rate set and the legacy PPDU format may be used.

When HT20 devices are present, only 20MHz PPDU formats may be used.

During the 40MHz phase of 20MHz-base managed mixed mode, only 40MHz PPDU formats may be used.

The MCS for a 20MHz PPDU format is selected not to exceed the Basic MCS capability for 20MHz operation.

1 The MCS for a 40MHz PPDU format is selected not to exceed the Basic MCS capability for
2 40MHz operation.
3 HT format PPDU shall be sent at a rate no higher than the HT Basic Rate specified in the HT
4 Management Element.
5

6 **7.2.2 Multicast**

7 Multicast/broadcast frames in pure mode and control frames that need to be received by HT
8 devices only shall be selected from the Basic MCS set.

9 **7.2.3 MRA MCS Selection Rules**

10 When a STA transmits a MRA to multiple receivers, it shall ensure that the MRA is sent using
11 transmit parameters that should make the PPDU receivable by all receivers in the aggregate.
12 It has to respect their receiver capabilities and select a “lowest common” set of parameters that
13 should be consistent with reception at all these STAs.

14 **7.2.4 Short GI**

15 The SHORT GI TXVECTOR attribute shall only be set to 1 in unicast frames addressed to a
16 peer that declares support of the Short GI in the HT capabilities element.

17
18 The SHORT GI TXVECTOR attribute shall be set to 0 in all broadcast frames, and all MAC
19 protection frames.

20 **7.3 Quality of Service (QoS)**

21 **7.3.1 802.11e Requirements**

22 An HT device shall support the mandatory features of an 802.11e QSTA.
23 An HT device shall support the use of the Block ACK mechanism introduced in 802.11e.
24 Note: this document extends the 802.11e Block Ack by defining a compressed Block Ack
25 frame format, and rules for Full State and Partial State Block Ack operations. These are
26 defined in sections 6.2.3 and 2.4.

27 **7.4 Enhanced Block Acknowledgment**

28 **7.4.1 Introduction (Informative)**

29 This section specifies an enhancement to 802.11e Block Ack mechanism for use with HT frame
30 aggregation. The enhancement, called Partial State BA, adds an immediate response mechanism
31 to 802.11e Delayed BA, but without the complexity and scalability issue associated with 802.11e
32 Immediate BA. An immediate BA response provides many benefits, including improved QoS,
33 reduced buffering at both originator and recipient, and increased power saving by stations that
34 use APSD, as a station’s wake time is proportional to how long it has to wait for its data. The
35 complexity and scalability issue of 802.11e Immediate BA arises from the requirement to keep
36 persistent BA states on a per TID per destination basis, and have ready access to them to create
37 immediate responses. This is especially problematic for QAPs, since they need to support many
38 simultaneous QSTAs. Partial State BA resolves these issues by adding an entity that logically
39 lies below the 802.11e Delayed BA, which handles immediate response but is less resource
40 hungry.
41

7.4.2 Block Ack Negotiation

Block Ack session is established by exchanging the ADDBA request and response frames. The negotiation follows the same procedure as described by 802.11e, but use the Block Ack Parameter Set as defined in section 1.3.4.

If an HT recipient is capable of HT Immediate BA, it shall so indicate by setting the Block Ack Policy field in ADDBA response frame to 1. Otherwise, it shall set the Block Ack Policy field in ADDBA response frame to 0, which indicates that it is capable of HT Delayed BA with Immediate Partial State Response, as defined in this section. HT Delayed BA with Immediate Partial State Response is the minimum required BA capability for an HT STA.

An HT recipient shall use the Buffer Size field to indicate how many outstanding MSDUs it can accept. This defines the BA window size, which is fixed for the life time of the BA session. An HT originator must take care not to overflow the BA window, i.e., not to transmit sequence numbers that are later than (Buffer Size + the earliest unacknowledged sequence number). Within the BA window, an HT originator may send sequence numbers in arbitrary order.

Buffer Size also defines the maximum value of NumMSDU_M1 for compressed MPDU, which is (Buffer Size – 1). An HT STA shall always transmit a compressed BA MPDU to a HT STA. An HT STA shall never transmit a compressed BA MPDU to a non-HT STA.

7.4.3 Immediate BA Response

With the introduction of A-MPDU aggregation and MMP, the meaning of immediate BA response is modified as follows.

During an MMP sequence immediate BA responses, if any, are transmitted at the start of the scheduled response period for the recipient.

When multiple SIFS-separated PPDU are transmitted by the originator in a TXOP (not within an MMP sequence), BAR are only permitted in the final PPDU of the burst. The recipient responds with immediate BA responses if any, SIFS duration after the final PPDU.

7.4.4 Explicit and Implicit BAR

There are two methods that an HT originator can use to solicit BA response from an HT recipient. One is the same as 802.11e, which is to send QoS Data frames with Ack Policy field in the QoS Control header set to Block Ack, and send BAR frames to request a response from the HT recipient. This is the explicit BAR mechanism. BAR may be sent in the same A-MPDU as the QoS Data frames, or in a separate MPDU or A-MPDU. Multiple BAR for different TID may be sent in the same A-MPDU. When multiple SIFS-separated PPDU are transmitted by the originator in a TXOP (not within an MMP sequence), BAR are only permitted in the final PPDU of the burst. If multiple immediate BA responses are generated, for instance, due to reception of multiple BAR for different TID, they shall be sent in a single A-MPDU.

When an HT originator discards frames due to MSDU lifetime being exceeded, it shall advance the sequence number past discarded frames. It should send an explicit BAR to resynchronize the starting sequence number of the BA window at the recipient. It may send new sequence numbers before or together with the explicit BAR.

The other method is used for QoS Data frames sent in an A-MPDU. QoS Data frames in an A-MPDU may be sent with Ack Policy field in the QoS Control header set to Normal Ack. If an HT recipient receives a QoS Data frame with Normal Ack policy in an A-MPDU, it shall interpret it as if there is an implicit BAR frame in the same A-MPDU for the same TID, and send a BA response accordingly. This is the implicit BAR mechanism, which is more robust than explicit BAR, as any valid frame received by the recipient will generate an immediate BA response. The HT originator should mark all QoS Data frames belonging to the same TID in an A-MPDU with the same Ack Policy. When multiple SIFS-separated PPDU are transmitted by the originator in a TXOP (not within an MMP sequence), implicit BAR are only permitted in the final PPDU of the burst.

Implicit BAR differs from explicit BAR in one aspect. Explicit BAR carries a Block Ack Starting Sequence Control, which indicates to the recipient that it must align the starting sequence number of its BA window. Implicit BAR carries no such information, therefore does not causes such alignment in the recipient.

Since the explicit BAR provides these additional capabilities, the originator is only permitted to include either an implicit or an explicit BAR but not both, for any delayed BA TID. Without this restriction, the originator cannot determine whether the immediate partial state BA response acknowledges the explicit BAR and thus whether the recipient has moved up the left edge of the BA window.

For immediate BA TID, the originator can determine whether the recipient has moved up the left edge of the BA window from the immediate full state BA response, so the originator is permitted to include both implicit and explicit BAR.

In this section, whenever BAR is mentioned, it shall be either explicit or implicit, unless a restriction is specifically stated.

7.4.5 Operation of HT Immediate BA

An HT STA that supports HT Immediate BA shall operate according to the 802.11e spec, with the additional rules regarding compressed BA and implicit BAR. It needs to keep a persistent BA state for each BA agreement that is accessible for creating immediate responses. When an HT recipient receives a BAR, it shall respond with a BA in SIFS time.

7.4.6 Operation of HT Delayed BA with Immediate Partial State Response

An HT recipient that supports Delayed BA maintains two logically separate BA states: (1) 16 (one per TID) partial state bitmaps for exactly one TA, which is used for generating immediate partial state BA response; (2) a persistent state for each BA agreement, on a per destination per TID basis, which is used for generating delayed full BA response as well as for duplicate detection. The partial state operates like a sliding window, just as the corresponding persistent state, except that the partial state is reset every time the HT recipient receives QoS Data frames from a different HT STA. An HT recipient shall record the TA of the last QoS Data frame received, regardless of TID, in order to check whether a matching partial state exists.

When an HT recipient receives QoS Data frames in an A-MPDU, it shall update both the partial state and the corresponding persistent state. If there is no matching partial state, e.g., the TA of

received frame is different from the last recorded TA; it shall reset the partial state first and then perform the update. The update procedure is a set of sliding window operations as described in 802.11e spec.

When an HT recipient receives a BAR corresponding to a Delayed BA TID, it shall check whether a matching partial state exists. If so, it shall send an immediate partial state BA response, after updating the partial state if necessary. Multiple BAR for different TID will generate multiple immediate BA responses, which shall be sent in a single A-MPDU. If no matching partial state exists, it shall send an ACK, and later send a delayed BA based on the persistent state. Multiple BAR for different TID will generate a single ACK and multiple delayed BA, which can be sent together in an A-MPDU or separately. The delayed BA shall be sent at the earliest opportunity using the highest priority access category, similar to 802.11e. Full state delayed BA when transmitted by the recipient shall be ACK-ed by the originator as in 802.11e.

The general rule at the HT recipient is to update BA states, then send response if required. It should be noted that an implicit BAR will always generate a BA response rather than an ACK, since the partial BA state will be recreated based on the received A-MPDU, even if no matching partial BA state is found.

An HT recipient shall not send immediate and delayed BA in the same A-MPDU. This allows an HT originator to distinguish the two kinds of BA responses. A BA that comes when a HT originator is waiting for a SIFS response is an immediate BA and shall not be acknowledged. A BA that comes when an HT originator is not waiting for a SIFS response is a delayed BA and shall be acknowledged.

When an HT recipient receives a non-aggregated QoS Data MPDU with Ack Policy in the QoS Control header set to Normal Ack, it shall update both partial and persistent states, and send an ACK after SIFS time.

7.5 PSDU Length Limit Rules

A STA shall declare the maximum PSDU size that it can receive using the Maximum Rx PSDU Length capability field. The STA shall be able to receive PSDUs of length less than the indicated limit. When it receives a PSDU of length greater than the limit, it shall receive the first $2^{\text{Maximum Rx PSDU Length}}$ bytes and discard any remainder.

A STA shall form an aggregate for transmission such that all the MPDUs within the aggregate that are intended to be received by a particular STA shall be within the first $2^{\text{Maximum Rx PSDU Length}}$ bytes of the PSDU, using the limit declared by that STA.

7.6 HT PHY-SAP service operation

The encoding of the HT-SF supports transmission of non-aggregate PSDUs up to a limit of 3071B.

The MAC may transmit single A-MSDU frames of length exceeding 3071B using an A-MPDU aggregate containing a single frame.

1 An A-MPDU aggregate shall be transmitted using a HT format PPDU with the A-MPDU
2 TXVECTOR field set to 1.
3
4 On receiving a PSDU with the A-MPDU RXVECTOR field set to 1, the MAC shall use the A-
5 MPDU aggregation format to unpack the component MPDUs.⁷
6

7 **8 MAC sublayer management**

8 **8.1 Coexistence management**

9 **8.1.1 Receiver capabilities regarding legacy operation in the extension channel**

10 An HT AP or IBSS STA should be able to detect activity in the extension channel without being
11 able to receive legacy MPDUs in it. On detecting a possible legacy MPDU, the STA should
12 enable itself to receive in that extension channel in order to determine if a legacy BSS has
13 arrived on the extension channel. It is not necessary that this capability be available simultaneous
14 with operation on the control channel.

15 **8.1.2 Infrastructure BSS Operation**

16 **8.1.2.1 This section defines rules for operation of an infrastructure HT BSS** 17 **Operation**

18 The AP controls the operating mode and protection requirements of its STA through information
19 elements in the beacon.

20
21 When the HT AP detects a legacy STA in the control channel, it shall set the legacy protection
22 flag in the beacon, enter 20 MHz-base managed mixed mode, or attempt to find an alternative
23 channel using the procedures defined in section 8.2. When the HT AP detects a legacy STA in
24 the extension channel, it shall enter 20 MHz-base managed mixed mode or attempt to find an
25 alternative channel using the procedures defined in section 8.2.

26
27 When the HT AP detects a 20MHz-only capable HT device, it shall set the HT20 protection flag
28 in the beacon, enter 20 MHz-base managed mixed mode, or attempt to find an alternative
29 channel using the procedures defined in section 8.2.

30
31 The HT AP transmits its beacon containing an HT management element⁸. The beacon may be in
32 either a 20MHz HT PPDU or a legacy PPDU type.

33
34 Note, the use of a beacon in a 20MHz HT PPDU format with the legacy protection flag
35 unset is only suitable for managed installations where management procedures ensure
36 that legacy BSSs do not share the same channels as HT APs.

37
38 When the beacon is formatted as a legacy PPDU, the AP may receive association and probe
39 requests from legacy STAs. The AP shall respond to a legacy probe request with a legacy probe

⁷ Note, the PHY transports a whole number of symbols in an aggregate. The A-MPDU structure ensures that any trailing padding is discarded on reception.

⁸ This will stop other co-channel HT APs from considering the AP to be a legacy AP.

1 response. It shall respond to a legacy association request with a legacy association response.
2 The AP may choose to accept or deny the association request.

3
4 In the 20 MHz-base managed mixed mode, the AP transmits its beacon using the legacy PPDU
5 type. The beacon is transmitted on the control channel but for the purpose of reserving the
6 extension channel, an AP may send beacons also in the extension channel. Beacons in the
7 extension channel may cause legacy STAs to attempt association but the HT AP shall deny
8 association or may ignore those requests.

9 **8.1.2.2 Infrastructure STA Operation**

10 The operation of an infrastructure STA is controlled by the extension channel control, the legacy
11 protection flag and the HT20 flag contained in beacon or probe response frames.

12
13 A STA that is only capable of 20MHz operation ignores the extension channel control.

14
15 A STA that is capable of 40MHz operation uses the extension channel control to determine what
16 transmission widths are permitted and whether 20MHz-base managed operation is required, as
17 defined in section 8.1.2.3..

18
19 The legacy protection and HT20 protection flags read from the beacon affects the selection of a
20 basic rate and PPDU type as defined in section 7.2..
21

22 **8.1.2.3 20 MHz-Base Managed Operation**

23 This section describes a coexistence mechanism where a BSS operates in 20 MHz mode and
24 switches to a 40 MHz phase under the control of an HT AP. The HT AP reserves the 20MHz
25 control channel and the 20MHz extension channel in turn to start the 40 MHz phase and resets
26 the NAV in the 20MHz channels in the opposite order to start the 20 MHz phase. The process is
27 illustrated in Figure 16. Due to the protection of the 40 MHz period in both channels, it is
28 tolerant of overlapping BSSs on both 20MHz halves of a 40MHz channel.

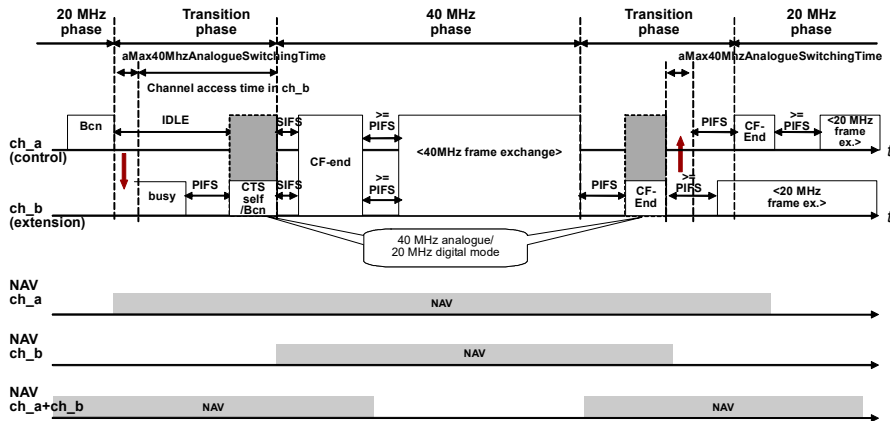


Figure 16 – 20 MHz-Base Managed Mixed Mode

8.1.2.3.1 Assumptions

20 MHz STAs associated with the HT AP operate only on the control channel.

8.1.2.3.2 Rules for Operation at HT AP

A CFP or a CTS-to-self NAV setting sent by an HT AP to reserve the medium for the 40 MHz phase shall include the transition periods between 20 and 40 MHz operation. If the HT AP intends to continue the CFP after the 40 MHz phase, it may do so by setting a longer duration for the CFP. To avoid an unexpectedly long channel access delay to the 40 MHz phase, the HT AP starts a timer with a timeout value equal to the extension channel access timeout after transmitting the beacon on the control channel. If the timer expires while attempting to reserve the extension channel, the AP shall abandon switching to the 40 MHz bandwidth by transmitting a CF-end frame on the control channel.

The AP shall wait for $aMax40MhzAnalogueSwitchingTime + PIFS$ before sending a CTS to self or a beacon in the extension channel to start the 40MHz operating phase. Likewise, it waits for $aMax40MhzAnalogueSwitchingTime + PIFS$ before sending out a CF-end in the control channel to start the 20 MHz operating phase (see Figure 17).

The HT AP exchanges frames with 40 MHz capable HT STAs using 40 MHz HT MCS in a 40 MHz phase. In a 20 MHz phase, it exchanges frames with legacy STAs using legacy rate and with both 20 MHz HT STAs and 40 MHz capable HT STAs using 20 MHz HT MCS. EDCA or HCCA channel access may be used in both phases.

8.1.2.3.3 Rules for Operation at 40 MHz capable HT STAs

A 40 MHz capable HT STA associated with the HT AP extends its channel bandwidth to 40 MHz when it receives a beacon frame that contains an Extension Channel Control subfield set to

3, interpreting the NAV value as the remaining duration of the 40 MHz phase. To recover from unexpectedly long channel access delay to the 40 MHz phase, it shall start a timer associated with a timeout value equal to the extension channel access timeout when receiving the beacon. This timeout is reset when a 40MHz CF-End is received. When the 40 MHz phase ends or the timer associated with the extension channel access timeout expires before the 40 MHz NAV is reset, it shall set the NAV for 40 MHz mode operation to 65535 TU and may switch back to 20 MHz mode on the control channel to communicate in the 20 MHz phase.

A 40 MHz capable HT STA shall only transmit frames during the 40 MHz phase using 40 MHz HT PPDU type and shall only transmit frames during the 20 MHz phase using a 20 MHz (HT or legacy) PPDU type.

A 40 MHz capable HT STA including a HT AP that is attempting an EDCA channel access during a 40 MHz phase either freezes the backoff counter during 20 MHz operation and resumes the interrupted backoff during the next 40 MHz phase or selects a new random backoff at the start of the 40 MHz phase. If it is attempting a channel access during a 20MHz phase and a 40 MHz phase starts, it manages the backoff counter for the 20 MHz access likewise.

A 40MHz capable HT STA shall ignore the legacy protection and HT20 protection flags in the beacon during the 40MHz phase of 20 MHz-base managed mixed mode operation.

8.1.3 Ad-hoc (IBSS) Operation

Each STA maintains a table for STAs it can see according to the mode of operation of the STA. Stale entries in this table are removed by a timeout process. A STA can be classified as legacy if it is seen to transmit a legacy beacon without the HT elements (note, this also includes legacy APs). It is classified as a HT20 device according to its declared capabilities. The IBSS beacon shall be transmitted using a legacy PPDU type. The beacon shall indicate what types of protection are required according to its own observations of legacy and HT20 STA types in its vicinity.

Its own observations, plus the protection requirements contained in received beacons shall be used to select the basic rates and PPDU types as defined in section 7.2.

8.2 Channel management

8.2.1 Channel Management at the AP

The AP transmits a beacon containing the Permitted Width Set, Control Channel Number, Extension Channel offset HT Management Element, as defined in section 6.3.2. This defines which channel is the control channel, which is the extension channel, and whether 40MHz operation is supported in this BSS.

An HT AP shall receive the beacons of other HT BSSs on its channel. If one of these indicates a that only 20MHz transmissions are permitted, the AP shall indicate that only 20MHz transmissions are permitted so that it matches or shall select a new operating channel. HT BSSs shall only overlap HT BSSs with the same control channel and extension channel location.⁹

⁹ This, together with the requirement for the same basic width set ensures that any pure-mode control frames sent in one BSS can be received in any overlapping HT BSS.

8.2.2 Channel Management at the STA

A STA shall only transmit 40MHz PPDU's when the Extension Channel Control is set to 1 (static 40MHz operation is permitted) or set to 3 (during the 40MHz phase of 20MHz-base managed mixed mode).

A STA shall only transmit an HT PPDU to a peer STA using a width that it knows the peer to support.

8.2.3 Channel Selection Rules for HT AP

The HT AP shall either be configured manually or configure itself automatically as described in this section.

The HT AP shall scan its environment before selecting channel parameters.

If the selected channel parameters overlap an existing HT BSS, then they must use the same control channel and extension channel offset and width (determined from the Extension Channel Control).

The AP shall reselect new channel parameters if an HT BSS that does not have the same control channel, extension channel offset and width starts operating on an overlapped channel.

Given a choice of 40MHz channel selections permitted by the previous rules, the AP should prefer a channel selection that aligns its 40MHz channel with the starting (i.e. lowest frequency) pair of adjacent 20MHz channels within any band or sub-band plus zero or more times 40MHz.

Note: The purpose of this recommendation is to avoid introducing 20MHz "holes" between adjacent operating 40MHz BSS, thus making them unavailable for 40MHz operation.

8.3 Calibration

8.3.1 Introduction

Transmit beamforming can operate with or without calibration assistance from the receiver. Support for calibration is optional.

Differences in transmit and receive chains in a STA or AP destroy the inherent reciprocity of the over-the-air TDD channel. Calibration is helpful in order to remove differences in transmit and receive chains and enforce reciprocity in the observed baseband-to-baseband channels. A simple over-the-air calibration procedure effectively corrects for these differences. The calibration procedure ensures that the observed channel matrices in the two directions of the link are transposes of each other and thus renders the resultant channel reciprocal. Thus, if they are able to do so, STAs calibrate upon association. Calibration works for any square or non-square dimensionality, i.e., N_{TX} and N_{RX} greater than 1 and less than 5.

8.3.2 Procedure

A STA shall only initiate a calibration training frame exchange sequence with a device that has the "Calibration Supported" HT Capability set to 1.

The Calibration Training frame exchange sequence, illustrated in Figure 17: Calibration Procedure operates as follows:

- STA A transmits a Calibration Training MPDU (Position field = 0).

- In response, STA B transmits a Calibration Training MPDU (Position field = 1) after a SIFS interval, which includes the HT-LTF that allows STA A to estimate the channel matrices.
- In response, STA A transmits a Calibration Training MPDU (Position field = 2) after a SIFS interval, which includes the HT-LTF that allows a receiving STA B to estimate the channel matrices.

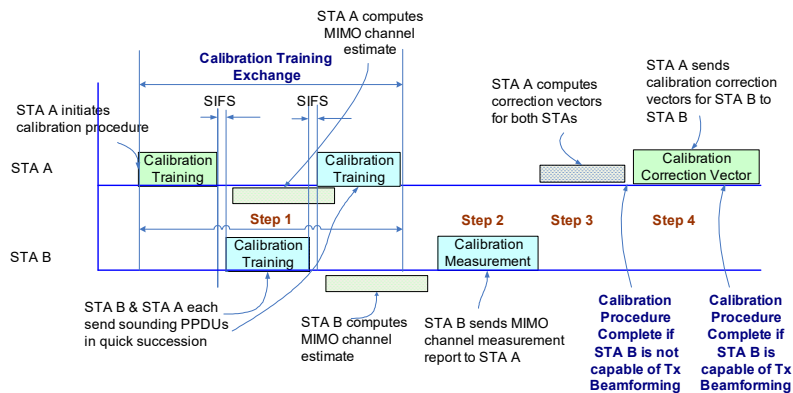


Figure 17: Calibration Procedure

The Calibration Training MPDUs are carried in non-aggregated sounding PPDU's. The last two steps must occur over a sufficiently short time interval so that the channel does not change over the interval. When used in a mixed BSS, this frame exchange sequence must be protected with an appropriate protection mechanism.

The remaining message exchange in the calibration procedure is not time critical. When the channel measurements become available at STA B, STA B sends one or more Calibration Measurement action frames that contain the MIMO Channel Measurement Report. STA B sets the Calibration Complete bit to '1' in case it is not capable of transmit beamforming. In this case STA A will not send Calibration Correction frame.

In case that both STAs are capable of transmit beamforming, once STA A has the MIMO Channel Measurement Report from STA B, along with its local channel measurement measured from the Calibration Training frame transmitted by STA B, STA A can compute the correction vectors required for both itself and STA B. The Calibration Correction frame is transmitted to complete the calibration procedure by STA A. The message includes the MIMO Correction Vector for STA B.

8.4 Precise TSF synchronization

8.4.1 Precise TSF synchronization support at the AP

Jitter of the beacon transmission time relative to its timestamp is created by its passage through both MAC and PHY.

1
2 The optional "Precise TSF synchronization" function provides a means to improve the precision
3 of synchronization of timestamps at a non-AP STA with those transmitted by the AP.

4
5 This is achieved by synchronizing the timing of the generation of PHY-TXSTART.request
6 primitive used to transmit a beacon with the update events ("clock edge") of the TSF timer, and
7 by minimizing the variation of PHY processing delay.

8
9 The amount of jitter between the TSF timer update and the on-the-air transmission time is
10 assumed to be a constant, which is a characteristic of the AP design. It is signaled in the
11 SyncPrecision field of the TSF Synchronization Precision Capability Element.

12
13 If Precise TSF synchronization is not supported, the AP shall not transmit the TSF
14 synchronization precision capability element.

15
16 If Precise TSF synchronization is supported, the AP shall transmit a TSF synchronization
17 precision capability element with the SyncPrecision field set to a non-zero value that is no less
18 than the actual precision available.

20 **8.4.2 Precise TSF synchronization support at the non-AP STA**

21 The precision of oscillators used for the TSF timers in both AP and STA, the variation of
22 multipath delay, as well as the transmission path jitter described in 8.4.1 are sources of jitter for
23 synchronizing TSF timers.

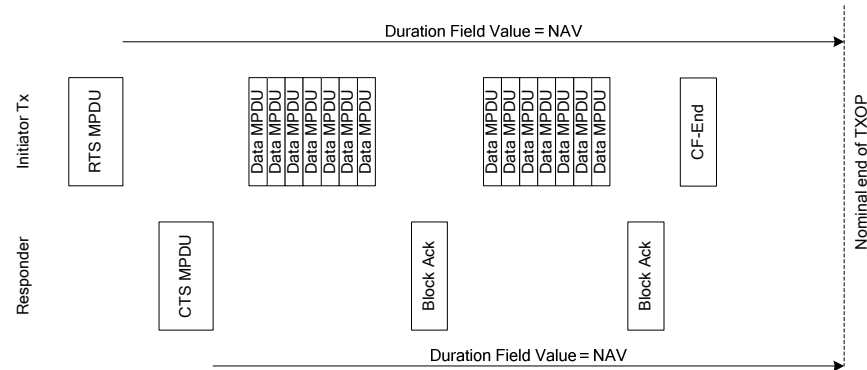
24
25 Transmission path jitter can be reduced at AP as described in 8.4.1. The Non-AP STA may
26 maintain a precise TSF timer by filtering out the above jitters using a PLL.

27
28 The implementation detail of the PLL is out of a scope of this standard.

9 Background information and Examples (Informative)

9.1 Example Aggregation Exchanges

9.1.1 Simple Aggregation Exchange



The initiator transmits a non-aggregate RTS using a basic rate and PPDU type (as defined in section 7.2), and with a NAV value set to the nominal end of the TXOP (this is LongNAV protection).

The responder transmits a non-aggregate CTS after a SIFS interval using a basic rate and PPDU type.

The initiator transmits an A-MPDU containing a burst of Data MPDUs addressed to the responder.

The responder determines this is an SRA (not part of an MMP sequence) and transmits a response after SIFS carrying only mandatory response frames. In this case only a single BA is required, which is sent in an unaggregated MPDU.

This sequence of Data burst / BA continues until the initiator has run out of data, or the TXOP expires. In this case, the initiator runs out of data, and transmits a CF-End at a basic rate and PPDU type.

9.1.2 Aggregation Exchange with Reverse-Direction Data and slow link adaptation

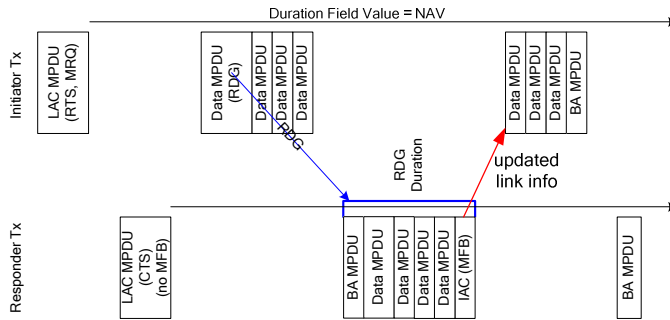


Figure 18 – LongNAV Bi-Directional Example

After an initial LAC (RTS)/LAC (CTS) MPDU exchange, the initiator transmits an aggregate containing one or more MPDUs with the RDG field set to 1. The duration value specifies a limit for the response burst. In this case the responder generates a single PPDU (with the More PPDU field set to 0 in all MPDUs) constrained by this duration, containing MPDUs addressed RA=initiator and containing QoS data AC matching that of the MPDU containing the RDG. The MRQ present in the first LAC generated no immediate response. The responder aggregated a LAC(MFB) later in the sequence in its response PPDU to contain updated link adaptation parameters.

9.1.3 MMP Sequence

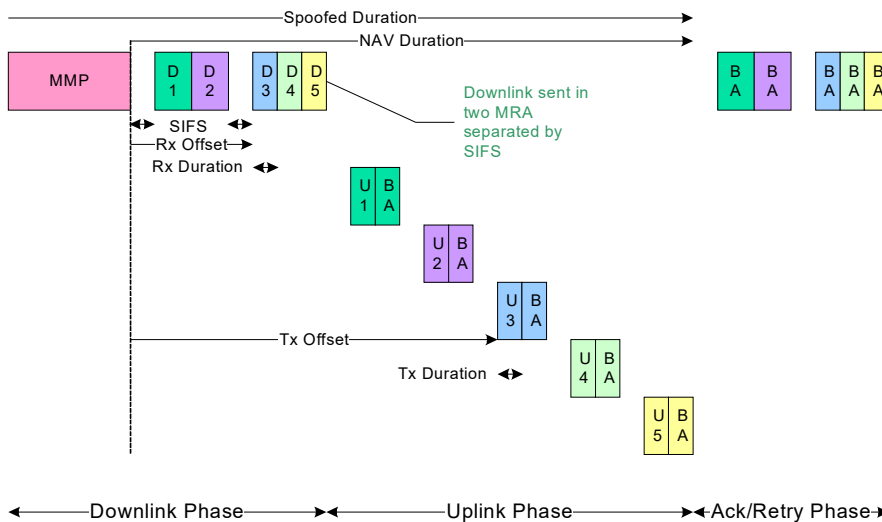


Figure 19: Example of an MMP sequence

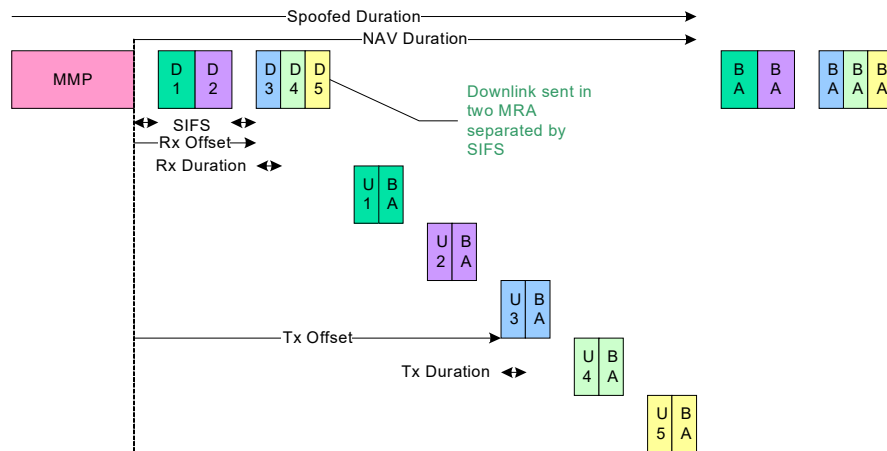


Figure 19: Example of an MMP sequence shows an example of the use of MMP, such as in support of VoIP handsets.

In this example, the AP has grouped together five handsets into one service interval. The five handsets all wake from sleep according to 802.11e periodic APSD. The AP transmits an MMP frame at the start of the service interval that locates the downlink (receive) and uplink (transmit) periods for each STA, identified through its association identifier.

In this case the downlink is split into two PPDU's containing five data MPDU's. STA with similar rates are grouped together to optimize the duration of the downlink. Each STA wakes to receive its downlink, and then wakes to transmit its uplink.

In this example, we show the use of data sent under a block ack agreement. So the transmitted data results in an implicit BAR, causing the uplink to contain data and acknowledgement to the downlink. It's also possible, in this example, to use normal ack policy because we are only transmitting at most one data frame for each receiver in each aggregate.

The five STA all awake at the end of the MMP sequence to receive the acknowledgements they are expecting to their uplink data (again, through the operation of the implicit BAR in this example). They stay awake until they receive their acknowledgements, or the service interval expires.

10 PHY-SAP service specification

The PHY service is provided to the MAC entry at an STA through the PHY service access point (PHY-SAP), as shown in Figure 11 of [1] and described in Clause 12 of that reference.

The amendments to the PHY-SAP parameters TXVECTOR and RXVECTOR are described in Sections 10.1.1 and 10.1.2 respectively.

10.1 PHY Specific Service Parameter List

The architecture of the IEEE 802.11 MAC is intended to be PHY independent. Some PHY implementations require PHY-dependent MAC state machines running in the MAC sublayer in order to meet certain PMD requirements. The PHY-dependent MAC state machine resides in a sublayer defined as the MAC sublayer management entity (MLME). In certain PMD implementations, the MLME may need to interact with the PLME as part of the normal PHY SAP primitives. These interactions are defined by the PLME parameter list currently defined in the PHY service primitives as TXVECTOR and RXVECTOR. The list of these parameters, and the values they may represent, are defined in the specific PHY specifications for each PMD. This subclause addresses the TXVECTOR and RXVECTOR for the MIMO-OFDM High Throughput (HT) PHY. The service parameters for TXVECTOR and RXVECTOR shall follow subclause 10.1.1 and 10.1.2.

10.1.1 TXVECTOR

The TXVECTOR is an array of fields sent from the MAC to the PHY instructing the PHY how to transmit the PPDU.

Parameter	Associated Primitive	Value
PPDU FORMAT	PHY-TXSTART.request (TXVECTOR)	Legacy 20 in 20 HT 20 in 20 Legacy upper 20 in 40 Legacy lower 20 in 40 HT upper 20 in 40 HT lower 20 in 40 HT 40 in 40
L-LENGTH	PHY-TXSTART.request (TXVECTOR)	1 – 4095
L-DATARATE	PHY-TXSTART.request (TXVECTOR)	6, 9, 12, 18, 24, 36, 48, and 54 (Support of 6, 12, and 24 data rates are mandatory.)
L-SERVICE	PHY-TXSTART.request (TXVECTOR)	Scrambler initialization; 7 null bits + 9 reserved null bits
TX_PWR_LEVEL	PHY-TXSTART.request (TXVECTOR)	1 – 8
HT-LENGTH	PHY-TXSTART.request	1 – 262143

	(TXVECTOR)	
MCS	PHY-TXSTART.request (TXVECTOR)	0 – 126
ADV CODING	PHY-TXSTART.request (TXVECTOR)	0, 1
SOUNDING	PHY-TXSTART.request (TXVECTOR)	0, 1
NLTF	PHY-TXSTART.request (TXVECTOR)	1 – 4
A-MPDU	PHY-TXSTART.request (TXVECTOR)	0, 1
SCRAMBLER-INIT	PHY-TXSTART.request (TXVECTOR)	0, 1, 2, 3
SHORT-GI	PHY-TXSTART.request (TXVECTOR)	0, 1
BEAMFORMED	PHY-TXSTART.request (TXVECTOR)	0, 1
BEAMFORM MATRIX	PHY-TXSTART.request (TXVECTOR)	$(N_{SD} + N_{SP})$ complex matrices of dimension $N_{TX} \times N_{LTF}$
STBC	PHY-TXSTART.request (TXVECTOR)	0, 1

Table 10: Table of parameters for the TX Vector

10.1.1.1 TXVECTOR PPDU FORMAT

The PPDU FORMAT field specifies whether the PPDU is to be sent using a legacy PPDU format or using a high-throughput format. Legacy is interpreted to be 802.11g if operating in the 2.4 GHz band and 802.11a if operating in the 5 GHz band. Furthermore, it specifies the channel (i.e, the full 20MHz channel, the upper 20MHz sub-channel in the 40MHz channel, the lower 20MHz sub-channel in the 40MHz channel, or the full 40MHz channel) at which the PPDU is to be sent.

The value of this field affects the interpretation of several other TXVECTOR fields.

10.1.1.2 TXVECTOR L-LENGTH

The allowed values for the L-LENGTH parameter are in the range of 1–4095.

In legacy format this parameter is used to indicate the number of octets in the MPDU which the MAC is currently requesting the PHY to transmit. This value is used by the PHY to determine the number of octet transfers that will occur between the MAC and the PHY after receiving a request to start the transmission. In high-throughput format this parameter (along with L-DATARATE) is used to protect the length of the current PPDU and possibly additional PPDUs.

1 **10.1.1.3 TXVECTOR L-DATARATE**

2 In legacy format the L-DATARATE parameter describes the bit rate at which the PLCP shall
3 transmit the PSDU. Its value can be any of the rates: 6, 9, 12, 18, 24, 36, 48, and 54. Data rates
4 of 6, 12, and 24 shall be supported; other rates may also be supported. In high-throughput format
5 this parameter (along with L-LENGTH) is use to protect the length of the current PPDU and
6 possibly additional PPDU. For legacy protection purposes, L-DATARATE in the L-SIG is set
7 to 6Mbps.
8

9 **10.1.1.4 TXVECTOR L-SERVICE**

10 In legacy format the L-SERVICE parameter consists of 7 null bits used for the scrambler
11 initialization and 9 null bits reserved for future use. In HT format this parameter is Null.
12

13 **10.1.1.5 TXVECTOR TXPWR_LEVEL**

14 The allowed values for the TXPWR_LEVEL parameter are in the range from 1–8. This
15 parameter is used to indicate which of the available TxPowerLevel attributes defined in the MIB
16 shall be used for the current transmission. In high-throughput format the transmit power is the
17 aggregate of the power from all transmit antennas.
18

19 **10.1.1.6 TXVECTOR HT-LENGTH**

20 The allowed values for this parameter are 1 – 264143. In HT format this parameter indicates the
21 number of octets in the PSDU to be sent in the PPDU. In legacy format this parameter is Null.
22

23 **10.1.1.7 TXVECTOR MCS**

24 The allowed values for this parameter are 0 – 126. In HT format this parameter indicates the
25 modulation and coding scheme. The number is an index into the MCS table given in Table 17.
26 In legacy format this parameter is Null.
27

28 **10.1.1.8 TXVECTOR ADV CODING**

29 In HT format this parameter indicates whether advanced coding is used. A value of 0 indicates
30 that advanced coding is not used. In legacy format this parameter is Null. A value of 1 indicates
31 LDPC coding is used.
32

33 **10.1.1.9 TXVECTOR SOUNDING**

34 In HT format this parameter indicates whether this PPDU is a sounding PPDU. A value of 0
35 indicates that it is not a sounding PPDU. A value of 1 indicates that it is a sounding PPDU. In
36 legacy format this parameter is Null.
37

38 **10.1.1.10 TXVECTOR NLTF**

39 In high-throughput format this parameter specifies the number of long training fields. In legacy
40 format this parameter is Null.

10.1.1.11 TXVECTOR A-MPDU

In high-throughput format this parameter indicates whether the PPDU contains an aggregated MPDU. A value of 0 indicates that the MPDU is not an aggregate and a value of 1 indicates that the MPDUs are aggregated. In legacy format this parameter is Null.

10.1.1.12 TXVECTOR SCRAMBLER-INIT

In high-throughput format this is the scrambler initialization field. It is a two-bit field, which serves as a pointer to one of four 7-bit long scrambler initialization sequences. In legacy format this parameter is Null.

The 2 bits are mapped to the following four scrambler initialization sequences:

b'00 → step 15 b'0111100
b'01 → step 84 b'0111101
b'10 → step 103 b'0111110
b'11 → step 127 b'0111111

Table 11: Scrambler Initialization Sequence

10.1.1.13 TXVECTOR SHORT-GI

In high-throughput format this parameter indicates whether the data is sent with a short guard interval (400 ns). A value of zero indicates a full GI (i.e. 800ns) and a value of 1 indicates a short GI (i.e. 400 ns). In legacy format this parameter is Null.

10.1.1.14 TXVECTOR BEAMFORMED

In high-throughput format this parameter indicates whether a beamforming matrix is applied to the data. A value of zero indicates that no beamforming is applied and a value of 1 indicates that beamforming is applied. In legacy format this parameter is Null.

10.1.1.15 TXVECTOR BEAMFORM MATRIX

In high-throughput format this field specifies $(N_{SD} + N_{SP})$ complex matrices of dimension $N_{TX} \times N_{LTF}$ which are used to beamform the PPDU. This field is only valid when the BEAMFORMED parameter is set to 1. In legacy format this parameter is set to Null.

10.1.1.16 TXVECTOR STBC

In HT format this parameter indicates whether STBC is used. A value of 0 indicates that STBC is not used. A value of 1 indicates that STBC is used. In legacy format this parameter is set to Null.

10.1.2 RXVECTOR

The RXVECTOR is an array of fields sent from the PHY to the MAC providing information regarding the received PPDU.

Parameter	Associated Primitive	Value
PPDU FORMAT	PHY-RXSTART.indicate (RXVECTOR)	Legacy 20 in 20 HT 20 in 20 Legacy upper 20 in 40 Legacy lower 20 in 40 HT upper 20 in 40 HT lower 20 in 40 HT 40 in 40
L-LENGTH	PHY-RXSTART.indicate (RXVECTOR)	1 – 4095
RSSI	PHY-RXSTART.indicate (RXVECTOR)	0 – RSSI maximum
L-DATARATE	PHY-RXSTART.indicate (RXVECTOR)	6, 9, 12, 18, 24, 36, 48, and 54
BW	PHY-RXSTART.indicate (RXVECTOR)	20, 40
HT-LENGTH	PHY-RXSTART.indicate (RXVECTOR)	1 – 262143
MCS	PHY-RXSTART.indicate (RXVECTOR)	0 – 126
ADV CODING	PHY-RXSTART.indicate (RXVECTOR)	0, 1
SOUNDING	PHY-RXSTART.indicate (RXVECTOR)	0, 1
NLTF	PHY-RXSTART.indicate (RXVECTOR)	1 – 4
A-MPDU	PHY-RXSTART.indicate (RXVECTOR)	0, 1
SHORT-GI	PHY-RXSTART.indicate (RXVECTOR)	0, 1
STBC	PHY-RXSTART.indicate (RXVECTOR)	0, 1

Table 12: Table of parameters for the RX Vector

10.1.2.1 RXVECTOR PPDU FORMAT

The PPDU FORMAT field specifies whether the received PPDU has a legacy PPDU format or a high-throughput format. Legacy is interpreted to be 802.11g if operating in the 2.4 GHz band and 802.11a if operating in the 5 GHz band. Furthermore, it specifies the channel (i.e, the full 20MHz channel, the upper 20MHz sub-channel in the 40MHz channel, the lower 20MHz sub-channel in the 40MHz channel, or the full 40MHz channel) at which the received PPDU was sent.

10.1.2.2 RXVECTOR L-LENGTH

The allowed values for the L-LENGTH parameter are in the range of 1–4095. This parameter is used to indicate the value of the L-LENGTH field in received PPDU. If this was a legacy PPDU then this parameter is the actual length of the PPDU. If this is a HT PPDU then this parameter, along with the L-DATARATE parameter, is used to calculate the protected duration.

10.1.2.3 RXVECTOR RSSI

The allowed values for the receive signal strength indicator (RSSI) parameter are in the range from 0 through RSSI maximum. This parameter is a measure by the PHY sub-layer of the energy observed at the antenna used to receive the current PPDU. RSSI shall be measured during the reception of the PLCP preamble. RSSI is intended to be used in a relative manner, and it shall be a monotonically increasing function of the received power. The value of RSSI is the maximum of the RSSI values from each receive antenna.

10.1.2.4 RXVECTOR L-DATARATE

The allowed values for L-DATARATE are: 6, 9, 12, 18, 24, 36, 48, and 54. This parameter is used to indicate the value of the L-DATARATE field in the received PPDU. If this is a legacy PPDU this is the data rate at which the data was transmitted. If this is an HT PPDU then this parameter, along with L-LENGTH, is used to calculate the protected duration.

10.1.2.5 RXVECTOR BW

In high-throughput format this parameter specifies whether the received PPDU is a 20 MHz bandwidth or 40 MHz bandwidth HT PPDU. In legacy format this parameter is Null.

10.1.2.6 RXVECTOR HT-LENGTH

The allowed values for this parameter are 1 – 264143. In HT format this parameter indicates the value contained in the HT-LENGTH field. This parameter specifies the number of octets to be transferred from the PHY to the MAC sub-layer. In legacy format this parameter is Null.

10.1.2.7 RXVECTOR MCS

The allowed values for this parameter are 0 – 126. The number is an index into the MCS table given in Table 17. In high-throughput format this parameter indicates the value of the MCS field in the PPDU HT-SIG. In legacy format this parameter is Null.

10.1.2.8 RXVECTOR ADV CODING

In HT format this parameter indicates whether advanced coding was used in the PPDU. A value of 0 indicates that advanced coding is not used. In legacy format this parameter is Null. A value of 1 indicates that LDPC coding is used.

10.1.2.9 RXVECTOR SOUNDING

In HT format this parameter indicates whether this PPDU is a sounding PPDU. A value of 0 indicates that it is not a sounding PPDU. A value of 1 indicates that it is a sounding PPDU. In legacy format this parameter is Null.

10.1.2.10 RXVECTOR NLTF

In high-throughput format this parameter specifies the number of long training fields. In legacy format this parameter is Null.

10.1.2.11 RXVECTOR A-MPDU

In high-throughput format this parameter indicates whether the PPDU contains an aggregated MPDU. A value of 0 indicates that the MPDU is not an aggregate and a value of 1 indicates that the MPDUs are aggregated. This value is used by the MAC sub-layer to indicate whether de-aggregation is required. In legacy format this parameter is Null.

10.1.2.12 RXVECTOR SHORT-GI

In high-throughput format this parameter indicates whether the data was sent with a short guard interval (400 ns). A value of zero indicates a full GI (800 ns) and a value of 1 indicates a short GI (400 ns). In legacy format this parameter is Null.

10.1.2.13 RXVECTOR STBC

In high-throughput format this parameter indicates whether STBC is used. A value of zero indicates that STBC is not used and a value of 1 indicates that STBC is used. In legacy format this parameter is set to Null.

11 MIMO-OFDM HT PHY specification

11.1 Overview

11.1.1 Introduction (Informative)

The PHY layer introduces several techniques for increasing the rate and reliability of the wireless link, as shown in Table 13:

Feature	Mandatory	Optional
Number of Spatial Streams	1 and 2	3 and 4
Number of Transmit Antennas	2	Greater than 2
Channelization bandwidth	20MHz	40MHz
Number of Occupied Subcarriers	56 in 20MHz	114 in 40MHz
Number of Data Subcarriers	52	108
Number of Pilot Subcarriers	4	6
Modulation Order	BPSK, QPSK, 16-QAM, 64-QAM	256-QAM
Code Rate	1/2, 2/3, 3/4, 5/6	
Guard Interval	800ns	400ns
Convolutional Coding	R=1/2, K=7, ($g_1=133_8$, $g_2=171_8$)	
LDPC		TX and RX Optional
TX Beamforming		TX and RX Optional
STBC		TX and RX Optional

Table 13: PHY Feature Set

11.1.1.1 Frequency Bands of Operation

Our proposal supports operation of devices in 2.4GHz, 5GHz, and 4.9GHz. Operation in 4.9GHz shall conform to 802.11j rules.

11.1.1.2 MIMO Data Path Overview

The general data path for MIMO transmission is shown in Figure 20.

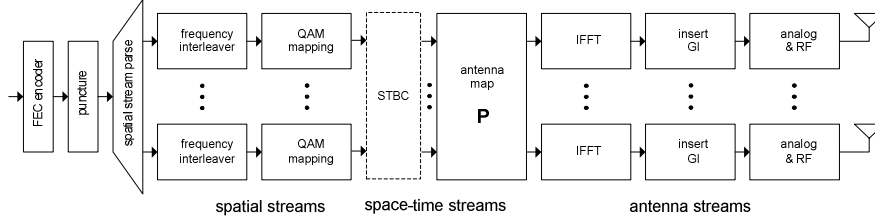


Figure 20: MIMO data path.

The FEC architecture has a single encoder. For the convolutional code (CC), the mother code is rate 1/2. Encoded bits may be punctured to produce code rates 2/3, 3/4 or 5/6. For the LDPC code different code rates are produced within the encoder and external puncturing is not applied. Processing of bits following encoding/puncturing is identical for both CC and LDPC.

The punctured bits are then distributed to N_{SS} spatial streams via the spatial stream parser. For each spatial stream, blocks of bits that map to a single OFDM symbol are interleaved. This interleaving step is called “frequency interleaving” because it results in bit interleaving across subcarriers. The frequency interleaver is similar to the 802.11a interleaver. The combination of the spatial stream parser and the frequency interleavers results in space-time interleaving.

Interleaved bits are then mapped to QAM constellation points. The mapping may be BPSK, QPSK, 16 QAM, 64 QAM or 256 QAM.

If STBC is in use, the modulation symbols from the N_{SS} spatial streams are encoded into $N_{STS} = 2N_{SS}$ space-time streams. If STBC is not used, the N_{STS} space-time streams are equal to N_{SS} spatial streams. The number of space-time streams is defined as

$$N_{STS} = \begin{cases} N_{SS} & \text{STBC is not used} \\ 2N_{SS} & \text{STBC is used} \end{cases}.$$

Antenna transformation maps N_{STS} space-time streams to N_{Tx} transmit antenna streams. Note that MIMO transmission requires $N_{SS} \leq \min\{N_{Tx}, N_{Rx}\}$ where N_{Rx} is the number of active receiving antennas at the receiving STA. In addition, we must always have $N_{STS} \leq N_{Tx}$ in the transmit data path. This transformation is generically represented by the matrix $\mathbf{P}$. In general, there may be a different $N_{Tx} \times N_{STS}$ transformation for each subcarrier. Our proposal supports three standard types of $\mathbf{P}$ -transformations, which are described in the subsections below.

Next, some mathematical notation for the antenna map transformations is provided. Let $\mathbf{P}^{(k)}$ denote the $N_{Tx} \times N_{STS}$ matrix that defines the antenna map for subcarrier k . We shall use the notation $\mathbf{p}_j^{(k)}$ to denote the j^{th} column of $\mathbf{P}^{(k)}$, and $p_{i,j}^{(k)}$ to denote the i,j^{th} element of $\mathbf{P}^{(k)}$. When convenient and when it is clear in context we shall often drop the subcarrier index superscript.

For an $N \times N$ matrix $\mathbf{A}$, the notation $[\mathbf{A}]_M$ shall denote the $N \times M$ matrix consisting of the first M columns of $\mathbf{A}$.

Steering matrices are orthonormal matrices. This means that the columns $\mathbf{p}_0 \cdots \mathbf{p}_{N_{STS}-1}$ have Euclidean norm 1 and are orthogonal to each other. Mathematically, the orthonormal property is equivalent to $\mathbf{P}^H \mathbf{P} = \mathbf{I}_{N_{STS} \times N_{STS}}$. In the case $N_{Tx} = N_{STS}$ an orthonormal matrix is said to be unitary, in which case we also have $\mathbf{P} \mathbf{P}^H = \mathbf{I}_{N_{Tx} \times N_{Tx}}$.

It is noted that non-singular MIMO transmission requires $N_{SS} \leq \min\{N_{Tx}, N_{Rx}\}$ where N_{Rx} is the number of active receive antennas at the receiving STA.

The PPDU has two parts. The legacy compatible part includes the L-STF, L-LTF, L-SIG and HT-SIG. The HT part includes the HT-STF, the HT-LTFs and the HT-Data. The antenna mapping for these two parts may be different. For example, the legacy compatible part may be direct map MIMO, while the HT part may employ spatial spreading or Tx beamforming. Indeed, both parts may employ spatial spreading, but with different cyclic delays.

To distinguish between different antenna map transformations, the notation $\mathbf{P}^{(k)}$ shall always denote the antenna map used during the HT part. The legacy compatible part always has only one spatial stream. Thus, we use a column vector $\mathbf{p}^{L(k)}$ to denote the antenna mapping for the legacy compatible part, and $p_{Tx}^{L(k)}$ is the element that defines the mapping to antenna i_{Tx} ($= 0, \dots, N_{Tx}$).

After the antenna map, antenna streams are transformed to the time domain via the IFFT. The cyclically extended GI (guard interval) is added. Finally, time domain windowing (not shown in Figure 20) is applied to create a continuous time-domain signal, and analog and RF processing yields the signals that are applied to transmit antennas.

Table 10 summarizes the OFDM parameters for 20 and 40 MHz channels in comparison to the legacy 802.11 a/g formats.

	802.11a/g (20 MHz)	20 MHz Channel (Mandatory)	40 MHz Channel (Optional)
FFT size	64	64	128
Number of data subcarriers	48	52	108
Number of pilot subcarriers	4	4	6
Subcarrier separation	312.5 kHz	312.5 kHz	312.5 kHz
Approx. Bandwidth	16.25 MHz	17.5 MHz	36.6 MHz

Table 14: Summary of OFDM parameters

11.1.1.2.1 Basic MIMO Overview

11.1.1.2.1.1 Direct Map MIMO Overview

Direct map MIMO is the simplest antenna mapping transformation. The $\mathbf{P}$ matrix is simply the identity mapping, i.e. each spatial stream maps to one antenna. Hence, there is a one-to-one correspondence between spatial streams and transmit antennas. Figure 21 illustrates the simplified data path for direct map MIMO.

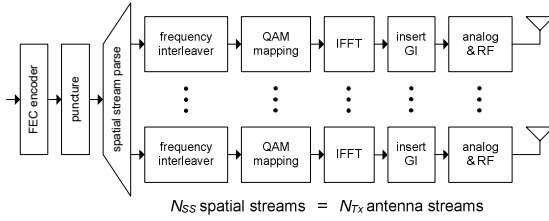


Figure 21: Direct Map MIMO.

For the direct map case, the $\mathbf{P}$ matrix is simply $\mathbf{P}^{(k)} = [\mathbf{I}_{N_{Tx} \times N_{Tx}}]_{N_{SS}}$; that is, we use the first N_{SS} columns of the $N_{Tx} \times N_{Tx}$ identity matrix. Notice that for $N_{SS} < N_{Tx}$, the bottom $N_{Tx} - N_{SS}$ rows of $\mathbf{P}^{(k)}$ are all zero, which means that $N_{Tx} - N_{SS}$ transmit chains are not active.

For the legacy compatible part, the direct map antenna map vector is just $\mathbf{p}^{L(k)} = [1 \ 0 \dots 0]^T$, which simply means the entire legacy compatible part is transmitted on the first antenna.

11.1.1.2.1.2 Spatial Spreading

Direct map MIMO only utilizes as many antennas as there are spatial streams; that is $N_{SS} = N_{Tx}$. Spatial spreading is one way to map spatial streams when the number of spatial streams is less than the number of transmitting antennas; that is $N_{SS} \leq N_{Tx}$.

The basic spatial spreading function is achieved using the first N_{SS} columns of a fixed $N_{Tx} \times N_{Tx}$ unitary matrix $\mathbf{W}$. The same matrix $\mathbf{W}$ is used for all subcarriers. Typically one uses the Walsh matrix for $N_{Tx} = 2$ and 4, or the Fourier matrix for $N_{Tx} = 3$. A problem with this basic spatial spreading function is that it can result in undesired beamforming effects. To mitigate this effect, time-domain cyclic delays are applied to OFDM symbols prior to GI insertion. The first antenna is not delayed. Linearly increasing cyclic delays are then applied to the remaining antennas. In addition to mitigating undesired beamforming, the cyclic delays can also yield some performance improvement via transmit diversity. Thus, the method is referred to as Cyclic Delay Diversity (CDD). Since the unitary spatial spreading matrix is typically the Walsh matrix, this method is often called “Walsh+CDD.”

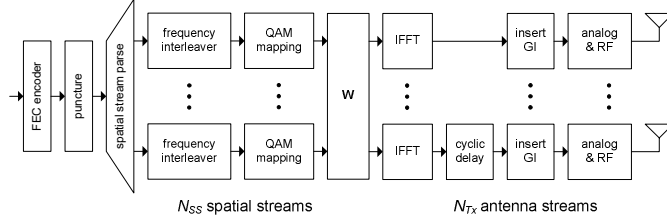


Figure 22: Time domain implementation of spatial spreading cyclic delay.

It is noted that since the $\mathbf{W}$ matrix is constant across subcarriers, yet another equivalent implementation would be to interchange the $\mathbf{W}$ matrix and the IFFT blocks.

At first, the spatial spreading method described above may seem to be a deviation to the general structure of Figure 20. However, there is a mathematical equivalence. The time domain cyclic delays are equivalent to a frequency dependent phase shift in the frequency domain. Each antenna has a different phasing due to the different cyclic delays. The result is that spatial spreading with time domain cyclic delays is mathematically equivalent to Figure 20 with $\mathbf{P} = \Phi\mathbf{W}$ where Φ is a frequency dependent diagonal phasing matrix.

Some mathematical notation for the antenna map transformations is provided. The frequency domain representation of the spatial spreading antenna map is

$$\mathbf{P}^{(k)} = \Phi^{(k)} \left[\mathbf{W}_{N_{Tx} \times N_{Tx}} \right]_{N_{SS}} \quad (1)$$

The matrix $\Phi^{(k)}$ is an $N_{Tx} \times N_{Tx}$ diagonal unitary matrix that captures the frequency domain equivalent of cyclic delays in the time domain. Let D denote the per antenna cyclic delay. The delay applied to antenna i_{Tx} is $(i_{Tx} - 1)D$. Then

$$\Phi^{(k)} = \text{diag} \left(1, \exp(-j2\pi k \Delta_F D), \dots, \exp(-j2\pi k (N_{Tx} - 1) \Delta_F D) \right). \quad (2)$$

The matrix $\mathbf{W}_{N_{Tx} \times N_{Tx}}$ is the unitary spreading matrix. For $N_{Tx} = 2$ or 4 these are Walsh-Hadamard matrices:

$$\mathbf{W}_{2 \times 2} = \frac{1}{\sqrt{2}} \begin{bmatrix} +1 & +1 \\ +1 & -1 \end{bmatrix} \text{ and } \mathbf{W}_{4 \times 4} = \frac{1}{2} \begin{bmatrix} +1 & +1 & +1 & +1 \\ +1 & -1 & +1 & -1 \\ +1 & +1 & -1 & -1 \\ +1 & -1 & -1 & +1 \end{bmatrix}. \quad (3)$$

For $N_{Tx} = 3$ we use the Fourier matrix

$$\mathbf{W}_{3 \times 3} = \frac{1}{\sqrt{3}} \begin{bmatrix} +1 & +1 & +1 \\ +1 & e^{j2\pi/3} & e^{-j2\pi/3} \\ +1 & e^{-j2\pi/3} & e^{j2\pi/3} \end{bmatrix}. \quad (4)$$

The unitary matrices in (3) and (4) are presented as typical solutions for construction of spatial spreading antenna map. In theory, any unitary matrix is sufficient. However, a significant advantage of these matrices is that each element has the constant complex modulus ($= 1/\sqrt{N_{Tx}}$). The significance of this property is that each spatial stream maps equal energy to each antenna. Thus equal power is delivered to each antenna.

For the legacy compatible part, the spatial spreading antenna map vector is

$$\mathbf{p}^{L(k)} = \Phi^{(k)}(D) \frac{1}{\sqrt{N_{Tx}}} \begin{bmatrix} 1 \\ \vdots \\ 1 \end{bmatrix} = \frac{1}{\sqrt{N_{Tx}}} \begin{bmatrix} 1 \\ \vdots \\ \exp(-j2\pi k(N_{Tx}-1)\Delta_F D) \end{bmatrix}. \quad (5)$$

This corresponds to a cyclic delay of $i_{Tx}D$ applied to antennas $i_{Tx} = 0, \dots, N_{Tx}-1$.

11.1.1.2.2 Space Time Block Coding

11.1.1.2.2.1 STBC with direct map MIMO

STBC with direct map MIMO only utilizes as many antennas as processed; that is $N_{Tx} = N_{STS}$. The $\mathbf{P}$ matrix is simply the identity mapping, i.e. each space-time stream maps to one antenna. Hence, there is a one-to-one correspondence between space-time streams and transmit antennas. Figure 23 illustrates the simplified data path for STBC with direct map MIMO.

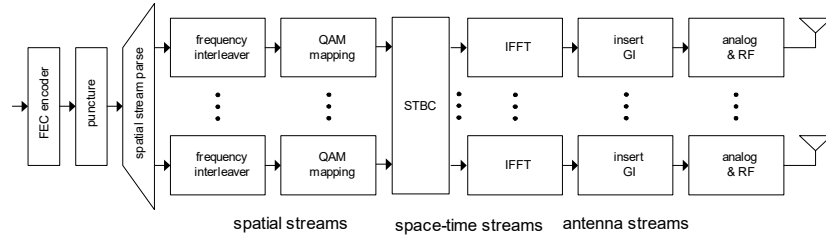


Figure 23: STBC with direct map MIMO

For the STBC with direct map case, the $\mathbf{P}$ matrix is simply $\mathbf{P}^{(k)} = [\mathbf{I}_{N_{Tx} \times N_{Tx}}]_{N_{STS}}$; that is, we use that first N_{STS} columns of the $N_{Tx} \times N_{Tx}$ identity matrix. Notice that for $N_{STS} < N_{Tx}$, the bottom $N_{Tx} - N_{STS}$ rows of $\mathbf{P}^{(k)}$ are all zero, which means that $N_{Tx} - N_{STS}$ transmit chains are not active.

For the legacy compatible part, the direct map antenna map vector is just $\mathbf{p}^{L(k)} = [1 \ 0 \dots 0]^T$, which simply means the entire legacy compatible part is transmitted on the first antenna.

11.1.1.2.2.2 STBC with spatial spreading

Spatial spreading is one way to map space-time streams to transmit antennas when the number of space-time streams is less than the number of transmitting antennas; that is $N_{STS} \leq N_{Tx}$. The

basic spatial spreading function is achieved using the first N_{STS} columns of a fixed $N_{Tx} \times N_{Tx}$ unitary matrix $\mathbf{W}$, which is described in Section 11.1.1.2.1.2.

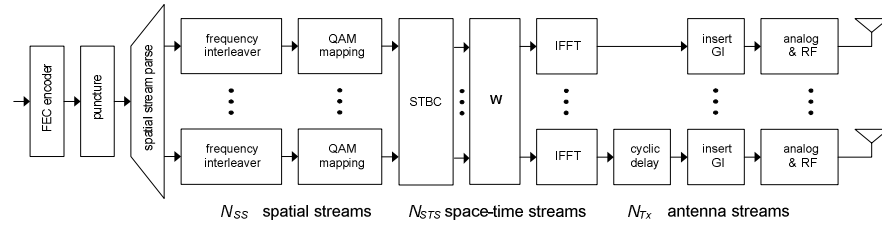


Figure 24: STBC with spatial spreading

The frequency domain representation of the spatial spreading antenna map is

$$\mathbf{P}^{(k)} = \Phi^{(k)} \left[\mathbf{W}_{N_{Tx} \times N_{Tx}} \right]_{N_{STS}} \quad (6)$$

The rest of the mathematical notation for the STBC with spatial spreading antenna map transformations is identical to that described in Section 11.1.1.2.1.2.

11.1.1.2.3 Transmit Beamforming

In this case, the P-transformation is designed specifically to pre-emphasize the dominant modes of transmission of the random MIMO channel. The optimal beamforming transformation is created from the right singular vectors of the SVD (singular value decomposition) of the observed channel. Our proposal provides full capability to implement SVD beamforming, as well as other types of beamforming such as constant amplitude phasing or constant beamforming matrices across all subcarriers. In these cases, the optimized beamforming matrix is the P-transformation.

Transmit beamforming is a technique that attempts to adjust the antenna map transformation to maximize the received energy at the receiver of each transmitted spatial stream. There are many ways to calculate beamforming matrices, which is largely left as an implementation option in this proposal. For informative purposes we briefly describe the optimal method based on the singular value decomposition (SVD) of the channel.

Let $\mathbf{H}^{(k)}$, which is an $N_{Rx} \times N_{Tx}$ matrix, denote the equivalent frequency domain channel for subcarrier k . Define $N = \min\{N_{Tx}, N_{Rx}\}$. Then the SVD is

$$\mathbf{H}^{(k)} = \mathbf{U}^{(k)} \mathbf{\Sigma}^{(k)} \mathbf{V}^{(k)H} \quad (7)$$

where $\mathbf{\Sigma}^{(k)} = \text{diag}(\sigma_0, \dots, \sigma_{N-1})$ is a diagonal matrix of “singular values,” $\mathbf{U}^{(k)}$ is an $N_{Rx} \times N$ orthonormal matrix, and $\mathbf{V}^{(k)}$ is an $N_{Tx} \times N$ orthonormal matrix. (Thus, $\mathbf{U}^{(k)}$ is unitary if $N_{Rx} = N$, and likewise $\mathbf{V}^{(k)}$ is unitary if $N_{Tx} = N$.) The singular values are non-negative real numbers. We may always assume (by permutation of columns of $\mathbf{U}^{(k)}$ and $\mathbf{V}^{(k)}$) that $\sigma_0 \geq \sigma_1 \geq$

1 $\dots \geq \sigma_{N-1}$. Given this ordering, the optimal beamforming transformation for $N_{ss} \leq N$ spatial
2 streams is

$$3 \quad \mathbf{P}^{(k)} = \left[\mathbf{V}^{(k)} \right]_{N_{ss}}. \quad (8)$$

5 11.1.1.3 PPDU Format for Basic MIMO Transmission

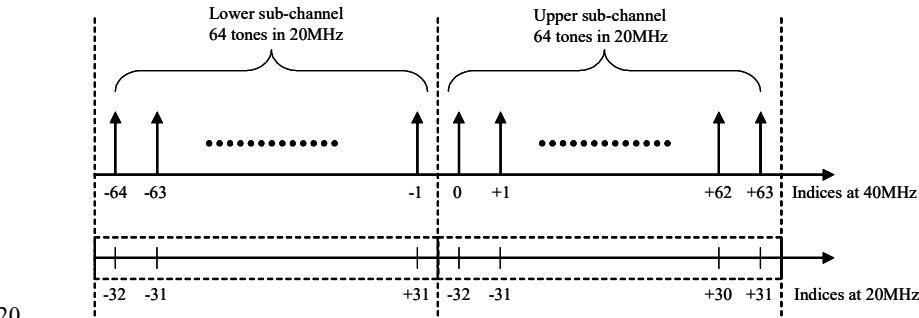
6 The generic PPDU format is shown in Figure 25:



9 **Figure 25: PPDU Format**

10 The L-STF (Legacy Short Training Field), the L-LTF (Legacy Long Training Field), L-SIG
11 (Legacy Signal Field) and HT-SIG (High Throughput Signal Field) comprise the legacy
12 compatible part of the PPDU preamble. HT-STF, the HT-STFs and HT-Data symbols comprise
13 the HT-Part of the PPDU.

14 In the 40MHz bandwidth, there are two 20MHz wide sub-channels. The upper sub-channel spans
15 from 0 to +63, and the lower sub-channel spans from -64 to -1, as shown in Figure 26. A
16 40MHz-HT device receiving a 20MHz-only transmission shall indicate to the MAC which sub-
17 channel is currently active.



20 **Figure 26: Upper and Lower sub-channel specification in 40MHz**

21 The PPDU format from two transmit antennas, each 40MHz wide, is shown in Figure 27.

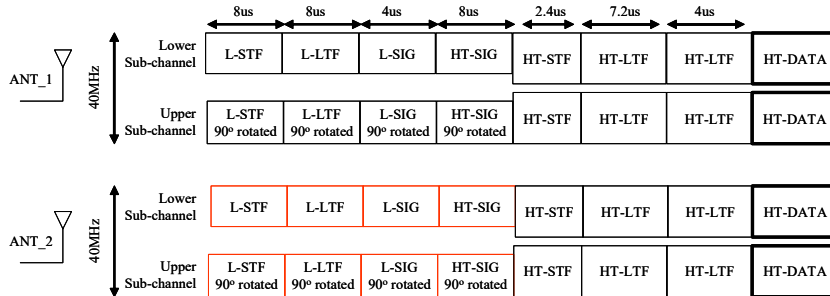


Figure 27: PPDU Format for 2x40 Basic MIMO Transmission¹⁰

The legacy part of the HT preamble (i.e. L-STF to L-SIG) and HT-SIG may either be transmitted from one antenna or both antennas. If transmitted from both antennas, the mapping of this single spatial stream to two antennas has to be such that beamforming in the far-field is mitigated. One method for achieving this is to use a cyclical delay diversity (CDD) mapping, as mentioned in 11.1.1.2.1.2. The optional part of the PPDU, corresponding to the CDD format, is shown in red color in Figure 27.

11.1.1.4 HT PCLP Preamble for Synchronization and Legacy Interoperability

The functions performed by the preamble include:

1. Start-of-Packet (SoP) detection
2. AGC
3. Coarse Frequency Offset Estimation
4. Coarse Timing Offset Estimation
5. Fine Timing Offset Estimation
6. Fine Frequency Offset Estimation
7. Channel Estimation

The High Throughput (HT) preamble in our proposal is a concatenation of the legacy preamble (identical to 802.11a/g) and a HT-specific preamble, as shown in Figure 28:

¹⁰ 40MHz operation by an HT device shall only be permitted in those regulatory domain that allow it.

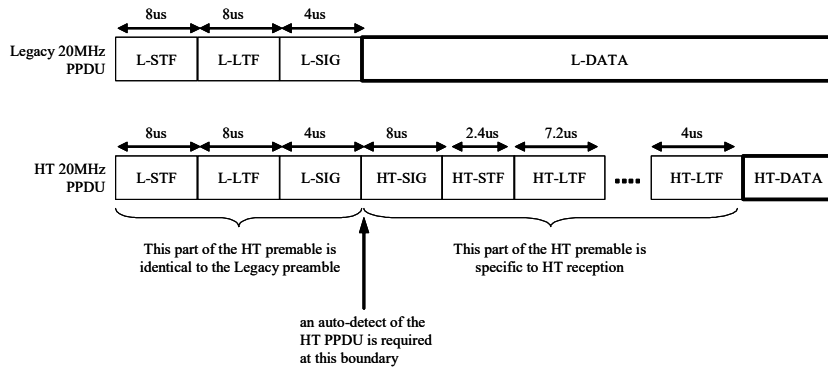


Figure 28: HT Preamble format

Concatenation of the legacy preamble allows PHY layer interoperability with 802.11a and ERP-802.11g modems.

A HT receiver does not know *a priori* whether it is receiving a legacy PPDU or a HT PPDU. Hence, a HT receiver has to perform an auto-detect after the legacy signal field (L-SIG) as to whether a HT-SIG is being received or legacy data (L-DATA). Our preamble format includes two provisions for auto-detecting the HT-SIG: (a) transmitting the HT-SIG as a BPSK signal on the quadrature axis instead of the in-phase axis, and (b) inverting the pilot polarity in going from the L-SIG to the HT-SIG.

The legacy part of the HT preamble allows a legacy receiver to properly decode the L-SIG. A HT receiver shall also perform functions 1 through 7 (SoP to Channel Estimation) to successfully decode the HT-SIG. It is anticipated that functions 1 through 4 (and perhaps function 5) are performed by the legacy short training field (L-STF), and functions 5 through 7 are performed by the legacy long training field (L-LTF).

Since a HT device (in our proposal) shall support multiple transmit antennas, the legacy part of the preamble can either be transmitted from one antenna or from multiple antennas. If more than one antenna is used for transmission, it is recommended that the signal be shifted in a cyclical fashion across the transmit antenna array. This technique introduces cyclical delay diversity (CDD), and it tends to reduce the “effective” length of the guard interval, as seen by a legacy device. Hence, the total shift across the transmit antenna array should be limited to 50ns.

In the 40MHz mode, the L-STF in the lower sub-channel is identical to legacy, whereas the L-STF in the upper sub-channel is a 90 degree phase rotation of the legacy STF. This rotation is performed to keep the PAPR of the STF low (see Figure 26 and Figure 27)

Since a legacy OFDM RX is not expected to “understand” any transmission after the L-SIG, the RATE and LENGTH fields in the L-SIG are selected such that a legacy OFDM RX can defer for the correct period of time.

The HT-SIG contains information needed to correctly de-map and decode the HT data field (i.e. the MIMO-OFDM symbols). It also contains fields for supporting advanced techniques that are described next.

Since the L-STF does not provide a sufficiently accurate power measurement for MIMO AGC purposes, a HT-STF has been introduced after the HT-SIG. The HT-STF is tone-interleaved symbol across the transmit antenna array. The HT short training symbol uses 24 tones in 20MHz (L-STF uses 12 tones in a 20 MHz channel). The choice of 24 tones permits accurate AGC measurements across 4 transmit antennas. In the 40 MHz channel, 48 tones are used in the HT-STF. The 24 (48) tones are interleaved across the antennas, i.e., 6 (12) tones are used per antenna if there are 4 transmitter antennas, and likewise 12 (24) are used per antenna if there are 2 transmitter antennas. The length of the HT-STF is 1.6 μ s. Since, the purpose of HT-STF is purely for AGC purposes, only one STS is needed. Together with the 0.8 μ s guard interval, the total length of the HT-STF is 2.4 μ s. The GI of the HT-STF, i.e. the first 0.8 μ s, would contain echoes from the previous symbol. Hence, a clean measurement of power is made in the 1.6 μ s portion of the HT-STF. It is anticipated that the RF transient settling after the AGC switch would occur in the GI of the HT-LTF that follows the HT-STF.

After the AGC has been “fine-tuned” for HT reception, channel estimation and fine frequency offset estimation are performed using the HT Long Training Symbols. In the basic MIMO modes, as in beamforming mode, the number of HT-LTFs sent must be at least equal to the number of streams sent, and at most equal to the number of transmit antennas. For example, when one spatial stream is transmitted using two transmit antennas, at least one HT-LTF must be sent, and under some conditions two HT-LTFs may be sent. However, if two spatial streams are sent using two transmit antennas, two HT-LTFs must be sent.

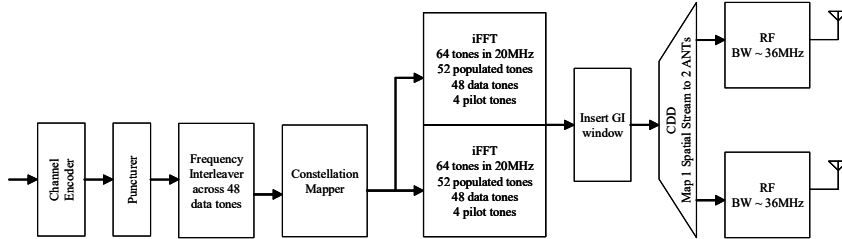
When the number of HT-LTFs that are sent is greater than the number of data streams, the resulting set of HT-LTFs is referred to as a segmented HT-LTF, and the additional HT-LTFs are referred to as extension HT-LTFs. In this case the tone interleaving is arranged so that the first N_{ss} HT-LTFs sound the MIMO channel used by the N_{ss} data streams, and the extension HT-LTFs sound the remaining dimensions of the MIMO channel. This is covered in more detail in 11.2.1.5.4.

The HT-LTF is also tone interleaved to minimize the power fluctuation with respect to the AGC setting (obtained via the HT-STF). Therefore, one HT-LTF would cover half of the tones in the two antenna case. Remaining tones are covered in the second HT-LTF. The first HT-LTF consists of two Long Training Symbols (LTS) as in 802.11a/g and a regular guard interval of 0.8 μ s, giving a total length of 7.2 μ s. When present, the second, third and fourth HT-LTFs each consist of a single HT-LTS with a regular guard interval of 0.8 μ s, giving a total length of 4 μ s.

11.1.1.5 Duplicate 6Mbps mode

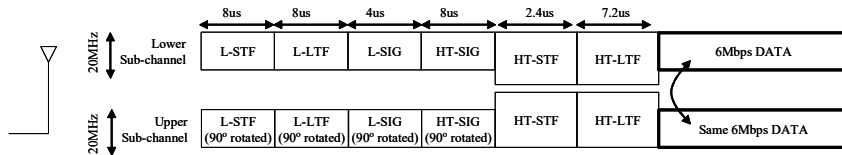
The lowest data rate in the 40MHz mode would be 13.5Mbps (= 6Mbps x 2.25), if independent information bits are mapped to the upper and lower sub-channels. A 6Mbps mode in 40MHz is obtained by duplicating the data from the lower sub-channel to the upper sub-channel. For the 6Mbps mode in 40MHz, the MPDU is encoded, punctured, interleaved, and constellation-

1 mapped as a 6Mbps transmission in 20MHz. The duplication is performed just prior to the iFFT
2 sub-carrier mapping, as shown in Figure 29.



3
4 **Figure 29: Transmitter configuration for 6Mbps in 40MHz¹¹**

5 Since the 6Mbps duplicate mode comprises of 1 spatial stream, only 1 HT-LTF is needed. Also
6 note that there is no tone-fill past the HT-SIG, unlike the regular 40MHz PPDU format show in
7 Figure 27. The PPDU format for the 6Mbps duplicate mode is shown in Figure 30:
8



9
10 **Figure 30: PPDU format for 6Mbps duplicate mode**

11 Pilot locations in the duplicate mode follow the pilot locations in the 20MHz mode. The
12 duplicate 6Mbps mode (in 40MHz) is signaled as mode 32 in the MCS set (see Table 17).

13 11.1.1.6 Feedback Mechanisms

14 Our proposal consists of several feedback mechanisms, supported at the MAC layer, as shown in
15 Table 15.

16

Nature of Feedback	Device Requirement	Type of Feedback	Description
Implicit feedback	Mandatory in device	Binary Response packet	- This only provides information to the TX whether its choice of the modulation-coding mode was supported by the channel. - Does not provide any information to help perform spatial shaping - Used when transmitting to legacy devices
Implicit Feedback	Optional	Binary Response packet sent as a sounding packet	Allows the Initiator to estimate the physical channel in the reverse link. If reciprocity can be assumed, and if the number of TX and RX antennas are identical at the recipient, the TX can use the derived CSI to perform spatial shaping (e.g. in the style of BF-MIMO)

¹¹ 40MHz operation by an HT device shall only be permitted in those regulatory domain that allow it.

Explicit Feedback	Mandatory	RR (Rate Recommendation) Response packet	- The response packet contains a rate recommendation to the TX - Since spatial shaping at the initiator is not desired, HT-LTFs are not appended
Explicit Feedback	Mandatory	RR Response packet sent as a sounding packet	- The response packet contains a rate recommendation to the TX - Response packet does not contain forward link Channel State Information (CSIT) - However, the sounding packet allows reverse link channel estimation. And, assuming reciprocity and equal number of TX RX antennas at the recipient, the initiator can perform spatial shaping.

Table 15: Feedback Mechanisms

11.1.1.7 Comparison among MIMO transmission modes

Our proposal supports three classes of MIMO Transmissions Modes, as outlined in Table 16:

MIMO Modes	Characteristic	Extent of TX adaptation
Basic MIMO (mandatory)	Antenna mapping: direct map or spatial spreading	- No adaptation is performed in the spatial domain - MCS selection (adaptation) is based upon either: (1) binary feedback (i.e. ACK/noACK), or (2) recommendation from the RX, or (3) availability of CSI at the TX
TX Beamforming (Optional)	- All spatial streams are spatially shaped via a beamforming matrix that may be different for each subcarrier. - Enhanced performance can be obtained through the use of optional MCSs which support different data rates across spatial streams.	- CSI is required at the TX - Sounding packet from the recipient to the initiator is required to estimate the CSI at the transmitter - RF calibration at transmitter side is required since reciprocity is used to perform TX beamforming - It is not mandated at devices which don't support Tx BF that they should be involved in calibration sequence.
Space Time Block Coding (Optional)	- All spatial streams undergo space-time block coding - STBC output streams undergo antenna mapping: direct map or spatial spreading	- HT-Data field must contain an even number of OFDM symbols - MCS selection (adaptation) is based upon either: (1) binary feedback (i.e. ACK/noACK), or (2) recommendation from the RX, or (3) availability of CSI at the TX

Table 16: MIMO Transmission options

11.1.1.8 “Modulation-Coding Scheme” (MCS) Sets

Our proposal augments the 802.11a MCS set through the use of multiple spatial streams and bandwidth extension. A set of MCSs is defined to take full advantage of the availability of multiple spatial streams and extended bandwidth. The complete set is shown in Table 17. Our proposal supports a mandatory data rate of 130 Mbps using two spatial streams in 20MHz channelizations. And, with an eye towards the future, our proposal introduces scalability to 4 spatial streams and 40MHz channelization, offering data rates in excess of 700Mbps.

The first 33 MCSs (MCS 0 through MCS 32) consist of 8 modulation/code rate combinations supporting 1, 2, 3, and 4 spatial streams, plus a 6 Mbps duplicate mode for 40 MHz operation. All of these MCSs have equal code rate and modulation on all active spatial streams. Support of MCS 0 through MCS 15 is mandatory. Support of the remaining MCSs is optional.

In order to match per stream code rates and modulations as closely as possible to channel conditions on each spatial stream in BF MIMO, it is necessary to include MCSs with different data rates on each spatial stream. This may also be useful for basic MIMO. BF MIMO also can benefit from the use of 256-QAM, which is not used in MCSs 0 – 32. MCSs 33 – 126 have unequal modulation and/or 256-QAM. In order to simplify channel encoding and spatial parsing, a single channel coding rate with different modulations is used across spatial stream. All of these MCSs are optional.

Table 17: MCS set

MCS Index	Code Rate	Stream Modulations				20 MHz Rates		40 MHz Rates	
		M0	M1	M2	M3	Full GI	Half GI	Full GI	Half GI
0	1/2	BPSK	OFF	OFF	OFF	6.50	7.22	13.50	15.00
1	1/2	QPSK	OFF	OFF	OFF	13.00	14.44	27.00	30.00
2	3/4	QPSK	OFF	OFF	OFF	19.50	21.67	40.50	45.00
3	1/2	16-QAM	OFF	OFF	OFF	26.00	28.89	54.00	60.00
4	3/4	16-QAM	OFF	OFF	OFF	39.00	43.33	81.00	90.00
5	2/3	64-QAM	OFF	OFF	OFF	52.00	57.78	108.00	120.00
6	3/4	64-QAM	OFF	OFF	OFF	58.50	65.00	121.50	135.00
7	5/6	64-QAM	OFF	OFF	OFF	65.00	72.22	135.00	150.00
8	1/2	BPSK	BPSK	OFF	OFF	13.00	14.44	27.00	30.00
9	1/2	QPSK	QPSK	OFF	OFF	26.00	28.89	54.00	60.00
10	3/4	QPSK	QPSK	OFF	OFF	39.00	43.33	81.00	90.00
11	1/2	16-QAM	16-QAM	OFF	OFF	52.00	57.78	108.00	120.00
12	3/4	16-QAM	16-QAM	OFF	OFF	78.00	86.67	162.00	180.00
13	2/3	64-QAM	64-QAM	OFF	OFF	104.00	115.56	216.00	240.00
14	3/4	64-QAM	64-QAM	OFF	OFF	117.00	130.00	243.00	270.00
15	5/6	64-QAM	64-QAM	OFF	OFF	130.00	144.44	270.00	300.00

MCS Index	Code Rate	Stream Modulations				20 MHz Rates		40 MHz Rates	
		M0	M1	M2	M3	Full GI	Half GI	Full GI	Half GI
16	1/2	BPSK	BPSK	BPSK	OFF	19.50	21.67	40.50	45.00
17	1/2	QPSK	QPSK	QPSK	OFF	39.00	43.33	81.00	90.00
18	3/4	QPSK	QPSK	QPSK	OFF	58.50	65.00	121.50	135.00
19	1/2	16-QAM	16-QAM	16-QAM	OFF	78.00	86.67	162.00	180.00
20	3/4	16-QAM	16-QAM	16-QAM	OFF	117.00	130.00	243.00	270.00
21	2/3	64-QAM	64-QAM	64-QAM	OFF	156.00	173.33	324.00	360.00
22	3/4	64-QAM	64-QAM	64-QAM	OFF	175.50	195.00	364.50	405.00
23	5/6	64-QAM	64-QAM	64-QAM	OFF	195.00	216.67	405.00	450.00
24	1/2	BPSK	BPSK	BPSK	BPSK	26.00	28.89	54.00	60.00
25	1/2	QPSK	QPSK	QPSK	QPSK	52.00	57.78	108.00	120.00
26	3/4	QPSK	QPSK	QPSK	QPSK	78.00	86.67	162.00	180.00
27	1/2	16-QAM	16-QAM	16-QAM	16-QAM	104.00	115.56	216.00	240.00
28	3/4	16-QAM	16-QAM	16-QAM	16-QAM	156.00	173.33	324.00	360.00
29	2/3	64-QAM	64-QAM	64-QAM	64-QAM	208.00	231.11	432.00	480.00
30	3/4	64-QAM	64-QAM	64-QAM	64-QAM	234.00	260.00	486.00	540.00
31	5/6	64-QAM	64-QAM	64-QAM	64-QAM	260.00	288.89	540.00	600.00
32 ¹	1/2	BPSK	OFF	OFF	OFF			6.00	6.67
33	3/4	256-QAM	OFF	OFF	OFF	78.00	86.67	162.00	180.00
34	1/2	16-QAM	QPSK	OFF	OFF	39.00	43.33	81.00	90.00
35	1/2	64-QAM	QPSK	OFF	OFF	52.00	57.78	108.00	120.00
36	1/2	64-QAM	16-QAM	OFF	OFF	65.00	72.22	135.00	150.00
37	3/4	16-QAM	QPSK	OFF	OFF	58.50	65.00	121.50	135.00
38	3/4	64-QAM	QPSK	OFF	OFF	78.00	86.67	162.00	180.00
39	3/4	64-QAM	16-QAM	OFF	OFF	97.50	108.33	202.50	225.00
40	3/4	256-QAM	QPSK	OFF	OFF	97.50	108.33	202.50	225.00
41	3/4	256-QAM	16-QAM	OFF	OFF	117.00	130.00	243.00	270.00
42	3/4	256-QAM	64-QAM	OFF	OFF	136.50	151.67	283.50	315.00
43	3/4	256-QAM	256-QAM	OFF	OFF	156.00	173.33	324.00	360.00
44	1/2	16-QAM	QPSK	QPSK	OFF	52.00	57.78	108.00	120.00
45	1/2	16-QAM	16-QAM	QPSK	OFF	65.00	72.22	135.00	150.00
46	1/2	64-QAM	QPSK	QPSK	OFF	65.00	72.22	135.00	150.00
47	1/2	64-QAM	16-QAM	QPSK	OFF	78.00	86.67	162.00	180.00
48	1/2	64-QAM	16-QAM	16-QAM	OFF	91.00	101.11	189.00	210.00

MCS Index	Code Rate	Stream Modulations				20 MHz Rates		40 MHz Rates	
		M0	M1	M2	M3	Full GI	Half GI	Full GI	Half GI
49	1/2	64-QAM	64-QAM	QPSK	OFF	91.00	101.11	189.00	210.00
50	1/2	64-QAM	64-QAM	16-QAM	OFF	104.00	115.56	216.00	240.00
51	1/2	256-QAM	QPSK	QPSK	OFF	78.00	86.67	162.00	180.00
52	1/2	256-QAM	16-QAM	QPSK	OFF	91.00	101.11	189.00	210.00
53	1/2	256-QAM	16-QAM	16-QAM	OFF	104.00	115.56	216.00	240.00
54	1/2	256-QAM	64-QAM	QPSK	OFF	104.00	115.56	216.00	240.00
55	3/4	16-QAM	QPSK	QPSK	OFF	78.00	86.67	162.00	180.00
56	3/4	16-QAM	16-QAM	QPSK	OFF	97.50	108.33	202.50	225.00
57	3/4	64-QAM	QPSK	QPSK	OFF	97.50	108.33	202.50	225.00
58	3/4	64-QAM	16-QAM	QPSK	OFF	117.00	130.00	243.00	270.00
59	3/4	64-QAM	16-QAM	16-QAM	OFF	136.50	151.67	283.50	315.00
60	3/4	64-QAM	64-QAM	QPSK	OFF	136.50	151.67	283.50	315.00
61	3/4	64-QAM	64-QAM	16-QAM	OFF	156.00	173.33	324.00	360.00
62	3/4	256-QAM	QPSK	QPSK	OFF	117.00	130.00	243.00	270.00
63	3/4	256-QAM	16-QAM	QPSK	OFF	136.50	151.67	283.50	315.00
64	3/4	256-QAM	16-QAM	16-QAM	OFF	156.00	173.33	324.00	360.00
65	3/4	256-QAM	64-QAM	QPSK	OFF	156.00	173.33	324.00	360.00
66	3/4	256-QAM	64-QAM	16-QAM	OFF	175.50	195.00	364.50	405.00
67	3/4	256-QAM	64-QAM	64-QAM	OFF	195.00	216.67	405.00	450.00
68	3/4	256-QAM	256-QAM	QPSK	OFF	175.50	195.00	364.50	405.00
69	3/4	256-QAM	256-QAM	16-QAM	OFF	195.00	216.67	405.00	450.00
70	3/4	256-QAM	256-QAM	64-QAM	OFF	214.50	238.33	445.50	495.00
71	3/4	256-QAM	256-QAM	256-QAM	OFF	234.00	260.00	486.00	540.00
72	1/2	16-QAM	QPSK	QPSK	QPSK	65.00	72.22	135.00	150.00
73	1/2	16-QAM	16-QAM	QPSK	QPSK	78.00	86.67	162.00	180.00
74	1/2	16-QAM	16-QAM	16-QAM	QPSK	91.00	101.11	189.00	210.00
75	1/2	64-QAM	QPSK	QPSK	QPSK	78.00	86.67	162.00	180.00
76	1/2	64-QAM	16-QAM	QPSK	QPSK	91.00	101.11	189.00	210.00
77	1/2	64-QAM	16-QAM	16-QAM	QPSK	104.00	115.56	216.00	240.00
78	1/2	64-QAM	16-QAM	16-QAM	16-QAM	117.00	130.00	243.00	270.00
79	1/2	64-QAM	64-QAM	QPSK	QPSK	104.00	115.56	216.00	240.00
80	1/2	64-QAM	64-QAM	16-QAM	QPSK	117.00	130.00	243.00	270.00
81	1/2	64-QAM	64-QAM	16-QAM	16-QAM	130.00	144.44	270.00	300.00
82	1/2	64-QAM	64-QAM	64-QAM	QPSK	130.00	144.44	270.00	300.00
83	1/2	64-QAM	64-QAM	64-QAM	16-QAM	143.00	158.89	297.00	330.00
84	1/2	256-QAM	QPSK	QPSK	QPSK	91.00	101.11	189.00	210.00

MCS Index	Code Rate	Stream Modulations				20 MHz Rates		40 MHz Rates	
		M0	M1	M2	M3	Full GI	Half GI	Full GI	Half GI
85	1/2	256-QAM	16-QAM	QPSK	QPSK	104.00	115.56	216.00	240.00
86	1/2	256-QAM	16-QAM	16-QAM	QPSK	117.00	130.00	243.00	270.00
87	1/2	256-QAM	16-QAM	16-QAM	16-QAM	130.00	144.44	270.00	300.00
88	1/2	256-QAM	64-QAM	QPSK	QPSK	117.00	130.00	243.00	270.00
89	1/2	256-QAM	64-QAM	16-QAM	QPSK	130.00	144.44	270.00	300.00
90	1/2	256-QAM	64-QAM	16-QAM	16-QAM	143.00	158.89	297.00	330.00
91	1/2	256-QAM	64-QAM	64-QAM	QPSK	143.00	158.89	297.00	330.00
92	1/2	256-QAM	256-QAM	16-QAM	QPSK	143.00	158.89	297.00	330.00
93	1/2	256-QAM	256-QAM	64-QAM	QPSK	156.00	173.33	324.00	360.00
94	1/2	256-QAM	256-QAM	256-QAM	QPSK	169.00	187.78	351.00	390.00
95	3/4	16-QAM	QPSK	QPSK	QPSK	97.50	108.33	202.50	225.00
96	3/4	16-QAM	16-QAM	QPSK	QPSK	117.00	130.00	243.00	270.00
97	3/4	16-QAM	16-QAM	16-QAM	QPSK	136.50	151.67	283.50	315.00
98	3/4	64-QAM	QPSK	QPSK	QPSK	117.00	130.00	243.00	270.00
99	3/4	64-QAM	16-QAM	QPSK	QPSK	136.50	151.67	283.50	315.00
100	3/4	64-QAM	16-QAM	16-QAM	QPSK	156.00	173.33	324.00	360.00
101	3/4	64-QAM	16-QAM	16-QAM	16-QAM	175.50	195.00	364.50	405.00
102	3/4	64-QAM	64-QAM	QPSK	QPSK	156.00	173.33	324.00	360.00
103	3/4	64-QAM	64-QAM	16-QAM	QPSK	175.50	195.00	364.50	405.00
104	3/4	64-QAM	64-QAM	16-QAM	16-QAM	195.00	216.67	405.00	450.00
105	3/4	64-QAM	64-QAM	64-QAM	QPSK	195.00	216.67	405.00	450.00
106	3/4	64-QAM	64-QAM	64-QAM	16-QAM	214.50	238.33	445.50	495.00
107	3/4	256-QAM	QPSK	QPSK	QPSK	136.50	151.67	283.50	315.00
108	3/4	256-QAM	16-QAM	QPSK	QPSK	156.00	173.33	324.00	360.00
109	3/4	256-QAM	16-QAM	16-QAM	QPSK	175.50	195.00	364.50	405.00
110	3/4	256-QAM	16-QAM	16-QAM	16-QAM	195.00	216.67	405.00	450.00
111	3/4	256-QAM	64-QAM	QPSK	QPSK	175.50	195.00	364.50	405.00
112	3/4	256-QAM	64-QAM	16-QAM	QPSK	195.00	216.67	405.00	450.00
113	3/4	256-QAM	64-QAM	16-QAM	16-QAM	214.50	238.33	445.50	495.00
114	3/4	256-QAM	64-QAM	64-QAM	QPSK	214.50	238.33	445.50	495.00
115	3/4	256-QAM	64-QAM	64-QAM	16-QAM	234.00	260.00	486.00	540.00
116	3/4	256-QAM	64-QAM	64-QAM	64-QAM	253.50	281.67	526.50	585.00
117	3/4	256-QAM	256-QAM	QPSK	QPSK	195.00	216.67	405.00	450.00
118	3/4	256-QAM	256-QAM	16-QAM	QPSK	214.50	238.33	445.50	495.00
119	3/4	256-QAM	256-QAM	16-QAM	16-QAM	234.00	260.00	486.00	540.00
120	3/4	256-QAM	256-QAM	64-QAM	QPSK	234.00	260.00	486.00	540.00
121	3/4	256-QAM	256-QAM	64-QAM	16-QAM	253.50	281.67	526.50	585.00

MCS Index	Code Rate	Stream Modulations				20 MHz Rates		40 MHz Rates	
		M0	M1	M2	M3	Full GI	Half GI	Full GI	Half GI
122	3/4	256-QAM	256-QAM	64-QAM	64-QAM	273.00	303.33	567.00	630.00
123	3/4	256-QAM	256-QAM	256-QAM	QPSK	253.50	281.67	526.50	585.00
124	3/4	256-QAM	256-QAM	256-QAM	16-QAM	273.00	303.33	567.00	630.00
125	3/4	256-QAM	256-QAM	256-QAM	64-QAM	292.50	325.00	607.50	675.00
126	3/4	256-QAM	256-QAM	256-QAM	256-QAM	312.00	346.67	648.00	720.00
127 ²	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

¹MCS 32 is used for 40 MHz duplicate mode to provide robust 6 Mbps operation in 40 MHz.
²The MCS index value 127 (binary value 1111111) is reserved to indicate a NULL response in the MCS field of an MFB.

11.1.1.8.1 MCS Capability Classes

A set of MCS capability classes is defined. These capability classes are used to specify which MCSs a STA supports on receive. MCS capability is specified independently for 20 MHz and 40 MHz. The capability classes are hierarchical in the number of streams supported: a capability class that supports n streams also supports 1 to $n-1$ streams.

The MCS capability classes are specified by a 4-bit field, $b_3b_2b_1b_0$, where:

- b_3 is set to 1 if MCSs that use 256-QAM are included, otherwise it is set to 0
- b_2 is set to 1 if MCSs with unequal modulations across spatial streams are included, otherwise it is set to 0
- b_1b_0 indicates the maximum number of spatial streams supported;
 - 00: maximum 1 stream
 - 01: maximum 2 streams
 - 10: maximum 3 streams
 - 11: maximum 4 streams

The capability classes are defined in Table 18 below.

Table 18: MCS capability classes

$b_3b_2b_1b_0$	Max Number of Streams	MCS	Description
0000	1	0 – 7	Constant modulation MCS only w/o 256-QAM, up to 1 stream
0001	2	0 – 15	Constant modulation MCS only w/o 256-QAM, up to 2 streams
0010	3	0 – 23	Constant modulation MCS only w/o 256-QAM, up to 3 streams
0011	4	0 – 31	Constant modulation MCS only w/o 256-QAM, up to 4 streams
0101	2	0–15; 34–39;	All MCS w/o 256-QAM, up to 2 streams
0110	3	0–23; 34–39; 44–50;	All MCS w/o 256-QAM, up to 3 streams

		55–61	
0111	4	0–31; 34–39; 44–50; 55–61; 72–83; 95– 106	All MCS w/o 256-QAM, up to 4 streams
1000	1	0–7; 33	All MCS w/256-QAM, up to 1 stream
1101	2	0–15; 33–43	All MCS w/ 256-QAM, up to 2 streams
1110	3	0–23; 33–71	All MCS w/ 256-QAM, up to 3 streams
1111	4	0–31; 33–126	All MCS w/ 256-QAM, up to 4 streams
0100, 1001–1100	--	N/A	RSVD

For 40MHz, all MCS capability class should include MCS 32.

Capability classes 0000 and 1000 specify MCSs with only one stream. While this proposal currently does not support single-stream devices, these single-stream capability classes are provided in anticipation of future support of single-stream devices.

Support of any MCS capability class requires support of all of the MCSs contained in that capability class.

11.2 PLCP Sublayer

11.2.1 Basic MIMO Mode

As described in Table 16, the basic MIMO mode does not involve any spatial steering. The basic MIMO mode can operate in both 20MHz and 40MHz channel bandwidths.

11.2.1.1 Basic MIMO PPDU format

The HT Physical layer defines a PPDU format that provides interoperability and coexistence with 802.11a stations and with ERP-OFDM stations of 802.11g at the link level without protection mechanisms. Figure 31 shows the PPDU format for the basic MIMO mode:

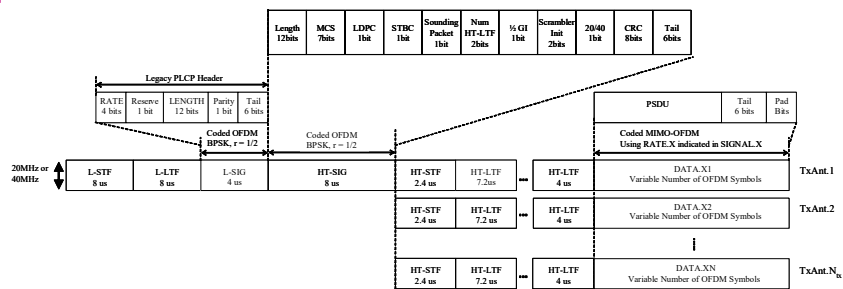


Figure 31: PPDU Format for N_{Tx} antennas

Commented [TT1]: HT-SIG contents need updating in this figure.

L-STF is the Legacy Short Training Field. Details of the L-STF symbols can be found in clause 11.2.1.5.1. The HT-STF is specific for HT. Details can be found in 11.2.1.5.3

L-LTF stands for Legacy Long Training Field. Details of the L-LTF symbols can be found in clause 11.2.1.5.2. The HT-LTFs are specific for HT and the details can be found in clause 11.2.1.5.4

L-SIG is based on the Legacy SIGNAL field as defined in clause 17.3.4 in [1]. The modulation and coding procedure also follows the steps of 17.3.4 in [1]. The RATE and LENGTH fields in L-SIG are defined in accordance with procedures described in 7.1.3.2 and 11.2.1.6.1.

The HT-SIG field is the signal field dedicated to the HT mode. The structure of this field is the same as the L-SIG. Since our proposal supports interoperability between HT devices and legacy OFDM devices at the PHY layer, a HT receiver will not know *a priori* whether a legacy packet or an HT packet is being received. That determination can only be made after the L-SIG. Our proposal supports two mechanisms for signaling a HT transmission: (a) send the HT-SIG as a BPSK signal on the quadrature axis, instead of on the in-phase axis, and (b) invert the polarity of the pilots in the HT-SIG with respect to the pilots in the L-SIG. These two mechanism allow an auto-detect of a HT transmission. Note that the pilots in the HT-SIG are not transmitted on the Quadrature axis. The definition of the contents of HT-SIG is specified in 11.2.1.6.2.

The L-STF, L-LTF, L-SIG, and HT-SIG should be transmitted from the antenna array such that an omni-directional beam pattern is created in the far field. This reduces the probability of creating hidden nodes in the BSS. One way to create an omni-beam is to transmit these fields from strictly one antenna. However, if the transmitter is power-amplifier limited, array gain can be derived by transmitting on multiple antennas. Since transmitting the same signal from multiple antennas invariably creates beamforming, one way to mitigate beamforming is to phase shift (i.e. time delay) the signal across the transmit antenna array. For an OFDM symbol, the delay can be introduced cyclically. Since delaying the same signal introduces frequency selectivity at the receiver, such a transmission is commonly referred to as “cyclical delay diversity” or CDD. This transmission format is shown in Figure 32:

Commented [TT2]: HT-SIG contents need updating in this figure as well.

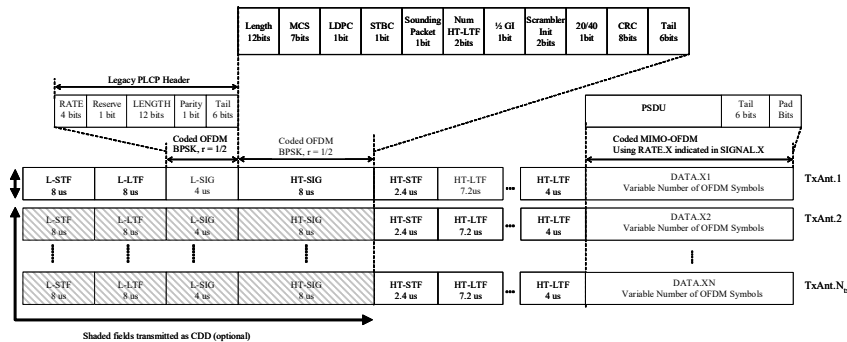


Figure 32: PPDU format leveraging CDD transmission

11.2.1.2 Legacy Protection

All MIMO transmissions are protected against legacy OFDM devices at the physical layer, and protected against legacy CCK/DSSS devices at the MAC layer. The legacy short training field, the legacy long training field and the legacy signal field are transmitted such that a legacy OFDM receiver (802.11g or 802.11a) is able to “understand” these fields. In the basic MIMO mode, the transmitter selects the Modulation Coding Scheme either based on conventional rate selection heuristics or via implicit or explicit feedback. Thus, the RATE and LENGTH fields in the legacy signal field can be used to allow the legacy OFDM receivers to correctly set their NAV.

RTS/CTS or CTS-to-self mechanism may be used to protect against legacy CCK/DSSS devices in an 802.11n BSS.

11.2.1.3 Timing related parameters

Parameter	Value for 20 MHz Channel	Value for 40 MHz Channel
N_{SD} : Number of data subcarriers	52	108
N_{SP} : Number of pilot subcarriers	4	6
N_{SN} : Number of center null subcarriers	1 (tone = 0)	3 (tones = -1,0,+1)
N_{SR} : Subcarrier range (index range)	28 (-28 ... +28)	58 (-58 ... +58)
Δ_F : Subcarrier frequency spacing	0.3125 MHz (= 20 MHz / 64)	0.3125 MHz (= 40 MHz / 128)
T_{FFT} : IFFT/FFT period	3.2 μ sec	3.2 μ sec
T_{GI} : GI duration	0.8 μ sec	0.8 μ sec
$T_{ShortGI}$: Short GI duration	0.4 μ sec	0.4 μ sec
T_{GI2} : Legacy Long Training symbol GI duration	1.6 μ sec	1.6 μ sec
T_{SYM} : Symbol interval	4 μ sec	4 μ sec
T_{L-STF} : Legacy STF duration	8 μ sec	8 μ sec
T_{L-LTF} : Legacy LTF duration	8 μ sec	8 μ sec
T_{L-SIG} : Legacy Signal Field duration	4 μ sec	4 μ sec
T_{HT-SIG} : HT Signal Field duration	8 μ sec	8 μ sec
T_{HT-STF} : HT Short training field duration	2.4 μ sec	2.4 μ sec
$T_{HT-LTF1}$: HT Long training field duration	7.2 μ sec	7.2 μ sec
$T_{HT-LTF2}$: HT Long training field duration	4 μ sec	4 μ sec
T_S : Nyquist sampling interval	50nsec	25nsec

Table 19: Timing Related Parameters

11.2.1.4 Mathematical Representation of Time Domain Signals

The transmitted signals will be described using the complex baseband signal notation. The transmitted signal at RF, $r_{RF}(t)$, is related to the complex baseband signal by the following relationship:

$$r_{RF}(t) = \text{Re}\{r(t)\exp(j2\pi f_c t)\} \quad (9)$$

where

$\text{Re}\{\cdot\}$ represents the real part of a complex variable;

f_c denotes the center frequency of the carrier.

The transmitted baseband signal consists of several subframes. The timing boundaries for the various subframes are shown in Figure 33.

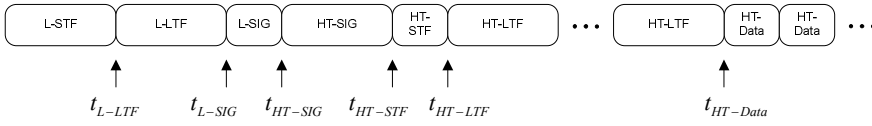


Figure 33: Timing boundaries for PPDU Fields

The signal transmitted on antenna i_{Tx} is

$$\begin{aligned} r_{PPDU}^{(i_{Tx})}(t) = & r_{L-STF}^{(i_{Tx})}(t) + r_{L-LTF}^{(i_{Tx})}(t - t_{L-LTF}) \\ & + r_{L-SIG}^{(i_{Tx})}(t - t_{L-SIG}) \\ & + r_{HT-SIG}^{(i_{Tx})}(t - t_{HT-SIG}) \\ & + r_{HT-STF}^{(i_{Tx})}(t - t_{HT-STF}) \\ & + r_{HT-LTF1}^{(i_{Tx})}(t - t_{HT-LTF1}) \\ & + \sum_{i_{LTF}=1}^{N_{LTF}-1} r_{HT-LTF2}^{(i_{Tx}, i_{LTF})}(t - t_{HT-STF} - T_{HT-LTF1} - i_{LTF} T_{HT-LTF2}) \\ & + r_{HT-Data}^{(i_{Tx})}(t - t_{HT-Data}) \end{aligned} \quad (10)$$

where

$$t_{L-LTF} = T_{L-STF}, \quad (11)$$

$$t_{L-SIG} = t_{L-LTF} + T_{L-LTF}, \quad (12)$$

$$t_{HT-SIG} = t_{L-SIG} + T_{L-SIG},$$

$$t_{HT-SIG} = t_{L-SIG} + T_{L-SIG}, \quad (13)$$

$$t_{HT-STF} = t_{HT-SIG} + T_{HT-SIG},$$

$$t_{HT-LTF} = t_{HT-STF} + T_{HT-STF} \quad (14)$$

and

$$t_{HT-Data} = t_{HT-LTF} + T_{HT-LTF} + (N_{LTF} - 1)T_{HT-LTF2}. \quad (15)$$

The time offsets t_{Field} determines the starting time of the corresponding subframe.

Each baseband waveform $r_{Field}^{(i_{Tx})}(t)$ is defined via the discrete Fourier transform as

$$r_{Field}^{(i_{Tx})}(t) = \frac{1}{\sqrt{N_{Field}^{Tone}}} w_{Field}(t) \sum_k X_k^{(i_{Tx})} \exp(j 2\pi k \Delta_F t) \quad (16)$$

This general representation holds for all fields, which are L-STF, L-LTF, L-SIG, HT-SIG, HT-STF, HT-LTF and HT-Data. The frequency domain symbols $X_k^{(i_{Tx})}$ define the field, as shall be specified in the following subsections. We adopt the convention that:

$$\sum_{i_{Tx}=0}^{N_{Tx}} E[|X_k^{(i_{Tx})}|^2] = 1 \quad (17)$$

With this convention, the $1/\sqrt{N_{Field}^{Tone}}$ scale factor in (16) ensures that the total power of the time domain signal as summed over all transmit antennas is 1. The following table summarizes the various values of N_{Field}^{Tone} .

Table 20: Number of tones for different fields.

Field	N_{Field}^{Tone}	
	20 MHz	40 MHz
L-STF	12	24
L-LTF	52	104
L-SIG	52	104
HT-SIG	52	104
HT-STF	24	48
HT-LTF	56	114
HT-Data	56	114
HT-Data 40 MHz Dup. Format	-	104

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- 3



7 11.2.1.5 Training symbols specification

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0 The L-STTS is identical to the 802.11a short training symbol. The legacy short training OFDM
1 symbol in the 20MHz mode is the L-STTS is

$$S_{-26,26} = \sqrt{1/2} \begin{pmatrix} 0, 0, 1+j, 0, 0, 0, -1-j, 0, 0, 0, 1+j, 0, 0, 0, -1-j, 0, 0, 0, -1-j, 0, 0, 0, 1+j, 0, 0, 0, \\ 0, 0, 0, 0, -1-j, 0, 0, 0, -1-j, 0, 0, 0, 1+j, 0, 0, 0, 1+j, 0, 0, 0, 1+j, 0, 0, 0, 1+j, 0, 0 \end{pmatrix}. \quad (18)$$

13

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$$S_{-58,58} = \sqrt{1/2} \{0, 0, 1 + j, 0, 0, 0, -1 - j, 0, 0, 0, 1 + j, 0, 0, 0, -1 - j, 0, 0, 0, -1 - j, 0, 0, 0, 1 + j, 0, 0, 0, 0, 0, 0, 0, -1 - j, 0, 0, 0, -1 - j, 0, 0, 0, 1 + j, 0, 0, 0, 1 + j, 0, 0, 0, 1 + j, 0, 0, 0, 1 + j, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, j - 1, 0, 0, 0, -j + 1, 0, 0, 0, j - 1, 0, 0, 0, -j + 1, 0, 0, 0, -j + 1, 0, 0, 0, j - 1, 0, 0, 0, 0, 0, 0, -j + 1, 0, 0, 0, -j + 1, 0, 0, 0, j - 1, 0, 0, 0, j - 1, 0, 0, 0, j - 1, 0, 0, 0, j - 1, 0, 0, 0, j - 1, 0, 0, 0\} \quad (19)$$

The tones in the upper subchannel (see Figure 26) are obtained by phase rotating the 802.11a short OFDM training symbol tones by 90 degrees, whereas the tones in the lower subchannel are identical to the 802.11a short training OFDM symbol tones. The 90° rotation helps keep the PAPR of the STF in 40MHz comparable to that in 20MHz.

$$r_{L-STF}^{(t_{rx})}(t) = \frac{1}{\sqrt{N_{L-STF}^{Tone}}} w_{L-STF}(t) \sum_{k=-N_{SR}}^{N_{SR}} p_{t_{rx}}^{L(k)} s_k \exp(j2\pi k \Delta_F t) \quad (20)$$

where we recall that $\mathbf{p}^{(L(k))}$ is the column vector that defines the antenna map for the legacy compatible part. Observe that equation (20) is identical to the general expression (16) with $X_k^{(i_{\text{rx}})} = p_{i_{\text{rx}}}^{(L(k))} S_k$.

27 The L-STs has a period of $0.8 \mu\text{s}$. The entire short training field includes ten such periods, with
28 a total duration of $T_{L-STF} = 8 \mu\text{s}$, hence there are 10 L-STs in the L-STF.

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- 28

The legacy long training OFDM symbol is identical to the 802.11a long training OFDM symbol. In the 20MHz mode, the long training OFDM symbol is given by

$$L_{-26,26} = \{1, 1, -1, -1, 1, 1, -1, 1, -1, 1, 1, 1, 1, -1, -1, 1, 1, -1, 1, 1, 1, 1, 0, 1, -1, -1, 1, 1, -1, 1, -1, -1, -1, -1, 1, 1, -1, -1, -1, 1, -1, 1, 1, 1, 1\}. \quad (21)$$

The legacy long training OFDM signal in the 40MHz mode is given by:

$$\begin{aligned}
L_{-ss,ss} = & \{1,1,-1,-1,1,1,-1,1,-1,1,1,1,1,1,-1,-1,1,1,-1,1,-1,1,1,1,0, \\
& 1,-1,-1,1,1,-1,1,-1,1,-1,-1,-1,-1,1,1,-1,-1,-1,1,1,1,0,0,0,0,0,0 \quad (22) \\
& 0,0,0,0,0,j,j,-j,-j,j,j,-j,j,-j,j,j,j,j,-j,-j,j,j,-j,-j,j,j,j,j,0, \\
& j,-j,-j,j,j,-j,j,-j,j,-j,-j,-j,-j,j,-j,-j,j,-j,-j,j,j,j,j\}
\end{aligned}$$

Tones in the upper subchannel (subcarriers +6 to +58) are obtained by phase rotating the 802.11a long OFDM training symbol tones by 90 degrees, whereas the tones within the lower subchannel (subcarriers -58 to -6) are identical to the 802.11a long OFDM training symbol tones. It should be noted that neither the legacy fields (L-STF, L-LTF, LSIG) nor the HT-SIG undergo any phase rotation in the lower subchannel. The subcarriers at ± 32 in 40MHz, which are the DC subcarriers for the legacy 20MHz transmission, are both nulled in the L-LTF. Such an arrangement allows proper synchronization of the 20MHz legacy device.

The L-LTF waveform is

$$r_{L-LTF}^{(i_{rx})}(t) = \frac{1}{\sqrt{N_{L-LTF}^{Tone}}} w_{L-LTF}(t) \sum_{k=-N_{SR}}^{N_{SR}} p_{i_{rx}}^{L(k)} L_k \exp(j 2\pi k \Delta_F (t - T_{2GI})) \quad (23)$$

where $T_{G12} = 1.6 \mu \text{ sec}$. Observe that equation (23) is identical to the general expression (16)

with $X_k^{(i_{Tx})} = p_{i_{Tx}}^{L(k)} L_k$.

Since $T_{L-LTF} = 8.0 \mu \text{ sec}$ and the symbol duration is $T_{FFT} = 3.2 \mu \text{ sec}$, we see that the L-LTF consists of a double GI followed by two full symbols.

11.2.1.5.3 HT-Short Training Field

The HT-STF follows the HT-SIG (see Figure 31), whose purpose it to “fine tune” the AGC for HT MIMO reception. Note that the first AGC operation is performed on the L-STF.

The HT-STS for 20MHz is

$$\begin{aligned}
HTS_{-26,26} = \frac{1}{\sqrt{2}} \left\{ \begin{aligned} &\{0, 0, 1+j, 0, -1-j, 0, 1+j, 0, -1-j, 0, -1-j, 0, 1+j, 0, 1+j, 0, 1+j, 0, -1-j, 0, -1-j, 0, \\ &0, 0, 1+j, 0, -1-j, 0, -1-j, 0, 1+j, 0, -1-j, 0, -1-j, 0, 1+j, 0, -1-j, 0, -1-j, 0, 1+j, 0, 0\} \quad N_{STS} = 1 \\ &\{0, 0, -1-j, 0, 1+j, 0, 1+j, 0, -1-j, 0, -1-j, 0, -1-j, 0, 1+j, 0, -1-j, 0, -1-j, 0, 1+j, 0, \\ &0, 0, 1+j, 0, -1-j, 0, -1-j, 0, 1+j, 0, -1-j, 0, -1-j, 0, 1+j, 0, 1+j, 0, -1-j, 0, 0\} \quad N_{STS} = 2 \\ &\{0, 0, -1-j, 0, -1-j, 0, 1+j, 0, 1+j, 0, 1+j, 0, 1+j, 0, 1+j, 0, -1-j, 0, -1-j, 0, -1-j, 0, \\ &0, 0, -1-j, 0, -1-j, 0, 1+j, 0, 1+j, 0, 1+j, 0, 1+j, 0, 1+j, 0, 1+j, 0, -1-j, 0, 0\} \quad N_{STS} = 3 \\ &\{0, 0, -1-j, 0, -1-j, 0, 1+j, 0, 1+j, 0, -1-j, 0, -1-j, 0, 1+j, 0, 1+j, 0, -1-j, 0, -1-j, 0, \\ &0, 0, -1-j, 0, -1-j, 0, -1-j, 0, 1+j, 0, 1+j, 0, -1-j, 0, -1-j, 0, 1+j, 0, 1+j, 0, -1-j, 0, 0\} \quad N_{STS} = 4 \end{aligned} \right. \quad (24)
\end{aligned}$$

2 The HT-STF for 40 MHz consists of 48 tones, and is given by:

$$\begin{aligned}
HTS_{-58,58} = \frac{1}{\sqrt{2}} \left\{ \begin{aligned} &\{0, 0, 1+j, 0, -1-j, 0, 1+j, 0, 1+j, 0, -1-j, 0, 1+j, 0, 1+j, 0, -1-j, 0, -1-j, 0, -1-j, 0, 1+j, 0, \\ &0, 0, 1+j, 0, -1-j, 0, -1-j, 0, 1+j, 0, -1-j, 0, -1-j, 0, 1+j, 0, 1+j, 0, -1-j, 0, -1-j, 0, 0, 0, 0, 0, 0, \\ &0, 0, 0, 0, 0, 0, 0, 0, -1-j, 0, -1-j, 0, 1+j, 0, -1-j, 0, -1-j, 0, 1+j, 0, -1-j, 0, -1-j, 0, 1+j, 0, 1+j, 0, \\ &0, 0, -1-j, 0, -1-j, 0, -1-j, 0, -1-j, 0, -1-j, 0, 1+j, 0, -1-j, 0, 1+j, 0, 1+j, 0, 1+j, 0, 0\} \quad N_{STS} = 1 \\ &\{0, 0, -1-j, 0, -1-j, 0, 1+j, 0, -1-j, 0, -1-j, 0, -1-j, 0, 1+j, 0, 1+j, 0, 1+j, 0, 1+j, 0, \\ &0, 0, 1+j, 0, -1-j, 0, 1+j, 0, -1-j, 0, 1+j, 0, 1+j, 0, -1-j, 0, -1-j, 0, 1+j, 0, -1-j, 0, 0, 0, 0, 0, \\ &0, 0, 0, 0, 0, 0, 0, 0, -1-j, 0, -1-j, 0, 1+j, 0, -1-j, 0, -1-j, 0, 1+j, 0, -1-j, 0, -1-j, 0, 1+j, 0, 1+j, 0, \\ &0, 0, 1+j, 0, 1+j, 0, 1+j, 0, -1-j, 0, -1-j, 0, -1-j, 0, -1-j, 0, 1+j, 0, -1-j, 0, -1-j, 0, 0\} \quad N_{STS} = 2 \\ &\{0, 0, -1-j, 0, -1-j, 0, -1-j, 0, 1+j, 0, 1+j, 0, -1-j, 0, -1-j, 0, -1-j, 0, -1-j, 0, -1-j, 0, 1+j, 0, \\ &0, 0, -1-j, 0, -1-j, 0, 1+j, 0, 1+j, 0, -1-j, 0, 1+j, 0, 1+j, 0, 1+j, 0, -1-j, 0, 0, 0, 0, 0, 0, \\ &0, 0, 0, 0, 0, 0, 0, 0, -1-j, 0, -1-j, 0, 1+j, 0, 1+j, 0, 1+j, 0, -1-j, 0, -1-j, 0, 1+j, 0, -1-j, 0, \\ &0, 0, 1+j, 0, 1+j, 0, -1-j, 0, -1-j, 0, -1-j, 0, -1-j, 0, 1+j, 0, -1-j, 0, -1-j, 0, -1-j, 0, 0\} \quad N_{STS} = 3 \\ &\{0, 0, -1-j, 0, -1-j, 0, 1+j, 0, 1+j, 0, 1+j, 0, -1-j, 0, -1-j, 0, 1+j, 0, 1+j, 0, -1-j, 0, -1-j, 0, \\ &0, 0, -1-j, 0, -1-j, 0, 1+j, 0, 1+j, 0, 1+j, 0, 1+j, 0, -1-j, 0, -1-j, 0, 1+j, 0, 1+j, 0, 0, 0, 0, 0, \\ &0, 0, 0, 0, 0, 0, 0, 0, 1+j, 0, 1+j, 0, -1-j, 0, -1-j, 0, 1+j, 0, 1+j, 0, 1+j, 0, -1-j, 0, -1-j, 0, \\ &0, 0, -1-j, 0, -1-j, 0, 1+j, 0, 1+j, 0, -1-j, 0, -1-j, 0, 1+j, 0, 1+j, 0, 1+j, 0, -1-j, 0, -1-j, 0, 0\} \quad N_{STS} = 4 \end{aligned} \right. \quad (25)
\end{aligned}$$

4 In the duplicate 6Mbps mode in 40MHz, the HT-STF shown in (25) is used, except for a scaling
5 factor change.

6
7 The HT-STF signal is then generated by the following rule.

$$\begin{aligned}
r_{HT-STF}^{(t_{Tx})}(t) &= \frac{1}{\sqrt{N_{HT-STF}^{Tone}}} w_{HT-STF}(t) \sqrt{N_{TX}} \\
&\sum_k q_{t_{Tx}, m(k) \% N_{STS}}^{(k)} HTS_k \exp(j2\pi k \Delta_F (t - T_{GI})) \quad (26)
\end{aligned}$$

where $T_{GI} = 0.8\mu s$ and N_{HT-STF}^{Tone} is the number of active tones (= 24 for 20 MHz and 48 for 40 MHz).

The range of the summation index k is defined as follows:

$$k = \begin{cases} -24, -22, \dots, -2 & 2, 4, \dots, 24 & \text{for 20 MHz} \\ -56, -54, \dots, -34 & -30, -28, \dots, -8 & 8, 10, \dots, 30 & 34, 36, \dots, 56 & \text{for 40 MHz} \end{cases}$$

which are the indices of the non-zero tones of HTS_k , and

$$m(k) = \begin{cases} \left. \begin{array}{ll} \frac{k+24}{2} & k \leq 0 \\ \frac{k+24}{2} - 1 & k > 0 \end{array} \right\} & \text{for 20 MHz} \\ \left. \begin{array}{ll} \frac{k+56}{2} & k \leq -34 \\ \frac{k+56}{2} - 1 & -30 \leq k \leq -8 \\ \frac{k+56}{2} - 8 & 8 \leq k \leq 30 \\ \frac{k+56}{2} - 9 & k \geq 34 \end{array} \right\} & \text{for 40 MHz} \end{cases}$$

Tone interleaving across space-time streams works as follows. HTS_k is non-zero for values of the tone index k . Define $m(k)$, which appears in the column subscript of the P-matrix. $m(k)$ runs through the integer values $0, \dots, N_{HT-STF}^{Tone} - 1$ as a function of k . Thus, $m(k) \% N_{STS}$, which defines the space-time stream used on tone index k , selects the corresponding column from the P-matrix. The two tables below identify the set of tones for each space-time stream.

N_{STS}	Set 0	Set 1	Set 2	Set 3
1	[-24:2:-2] [2:2:+24]			
2	[-24:4:-4] [2:4:24]	[-22:4:-2] [4:4:24]		
3	[-24:6:-6] [2:6:20]	[-22:6:-4] [4:6:22]	[-20:6:-2] [6:6:24]	
4	[-24:8:-8] [2:8:18]	[-22:8:-6] [4:8:20]	[-20:8:-4] [6:8:22]	[-18:8:-2] [8:8:24]

Table 21: Tone partitioning of HT-STF into sets for 20MHz (24 tones)

N_{STS}	Set 0	Set 1	Set 2	Set 3
1	[-56:2:-34] [-30:2:-8] [8:2:30] [34:2:56]			
2	[-56:4:-36] [-30:4:-10] [8:4:28] [34:4:54]	[-54:4:-34] [-28:4:-8] [10:4:30] [36:4:56]		
3	[-56:6:-38] [-30:6:-12] [8:6:26] [34:6:52]	[-54:6:-36] [-28:6:-10] [10:6:28] [36:6:54]	[-52:6:-34] [-26:6:-8] [12:6:30] [38:6:56]	
4	[-56:8:-40] [-30:8:-14] [8:8:24] [34:8:50]	[-54:8:-38] [-28:8:-12] [10:8:26] [36:8:52]	[-52:8:-36] [-26:8:-10] [12:8:28] [38:8:54]	[-50:8:-34] [-24:8:-8] [14:8:30] [40:8:56]

Table 22: Tone partitioning of HT-STF into sets for 40MHz (48 tones)

The HT-STF signal has a period of $1.6\mu s$, which is deemed sufficient for power measurement purposes. Since the HT-STF is tone-interleaved at the transmitter, the power periodicity of the HT-STF is also $1.6\mu s$.

11.2.1.5.4 HT-Long Training Field

The HT-LTFs are transmitted after the HT-STF. The number of HT-LTFs is equal to N_{LTF} . For any PPDU, there must be at least as many HT-LTFs as space-time streams in the HT Data portion of the PPDU, i.e. $N_{LTF} = N_{STS}$ (the number of space-time streams). For a sounding PPDU it is permissible for $N_{LTF} \geq N_{STS}$, because these PPDU provide channel measurement capability for potentially more spatial dimensions than the number of space-time streams. In the case that $N_{LTF} > N_{STS}$, the HT-LTFs are partitioned as data HT-LTFs and extension HT-LTFs. The data HT-LTFs are the first N_{STS} fields, which are indexed $i_{LTF} = 0, \dots, N_{STS} - 1$. The last $N_{LTF} - N_{STS}$ HT-LTFs are the extension fields, which are indexed $i_{LTF} = N_{STS} - 1, \dots, N_{LTF} - 1$. The result is referred to as a segmented HT-LTF. When a PPDU includes a segmented HT-LTF it is optional for a receiver to process the extension LTFs, however it is mandatory for a receiver to still process the data HT-LTFs and use these to decode HT-DATA in the normal manner.

As always, space-time streams are defined by columns of an orthogonal antenna map matrix $\mathbf{P}^{(k)}$, with the first N_{STS} columns defining the space-time streams used for data transmission, and the last $N_{LTF} - N_{STS}$ columns defining the extension space-time streams. Thus, for the purpose of defining HT-LTFs, $\mathbf{P}^{(k)}$ is an $N_{Tx} \times N_{LTF}$ dimension matrix.

The first HT-LTF consists of two Long Training Symbols (LTS) as in 802.11a/g and a regular guard interval of $0.8\mu s$, giving a total length of $7.2\mu s$. When present, the second and all subsequent HT-LTFs each consist of a single HT-LTS with a regular guard interval of $0.8\mu s$, giving a total length of $4\mu s$.

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$$\begin{aligned}
HTL_{-58,+58} = \{ & -1 \ 1 \ 1 \ 1 \ 1 \ -1 \ 1 \ 1 \ -1 \ -1 \ -1 \ 1 \ 1 \ 1 \ 1 \ 1 \ -1 \ 1 \ 1 \ -1 \ 1 \ -1 \ -1 \ -1 \\
& 1 \ 1 \ -1 \ -1 \ 1 \ 1 \ -1 \ -1 \ -1 \ 1 \ -1 \ 1 \ 1 \ -1 \ -1 \ 1 \ -1 \ 1 \ -1 \ -1 \ 1 \ 1 \ 1 \\
& 0 \ 0 \ 0 \ -1 \ -1 \ -1 \ -1 \ -1 \ -1 \ -1 \ -1 \ 1 \ 1 \ -1 \ 1 \ -1 \ 1 \ 1 \ -1 \ -1 \ 1 \ -1 \ -1 \ 1 \\
& -1 \ 1 \ -1 \ -1 \ -1 \ -1 \ 1 \ 1 \ -1 \ 1 \ -1 \ -1 \ 1 \ -1 \ 1 \ 1 \ -1 \ 1 \ -1 \ -1 \ 1 \ 1 \ 1 \}
\end{aligned} \tag{32}$$

2 In 40MHz, sequence 7 is:

[illegible]

4
5 In 40MHz, sequence 8 is:

[illegible]

7 In 40MHz, sequence 9 is:

$$HTL_{-58,+58} = \{-1\ 1\ -1\ -1\ 1\ 1\ 1\ -1\ 1\ 1\ 1\ -1\ 1\ 1\ 1\ 1\ -1\ -1\ -1\ -1\ -1\ -1\ -1\ -1$$

$$\quad 1\ -1\ -1\ -1\ -1\ 1\ 1\ -1\ -1\ 1\ 1\ 1\ 1\ -1\ 1\ -1\ -1\ 1\ 1\ 1\ 1\ 1\ -1\ -1\ -1\ 1\ 0$$

$$\quad 0\ 0\ -1\ 1\ 1\ -1\ -1\ -1\ -1\ 1\ 1\ 1\ -1\ 1\ 1\ -1\ -1\ -1\ 1\ -1\ -1\ -1\ -1\ -1\ 1\ 1\ -1$$

$$\quad -1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ -1\ -1\ -1\ -1\ 1\ 1\ -1\ 1\ 1\ 1\ -1\ -1\ 1\ -1\ -1\ 1\ 1\}$$
 (35)

The HT-LTF is generated similarly to the HT-STF. For the data HT-LTFs $i_{LTF} = 0, \dots, N_{STS} - 1$, the signal is

$$r_{HT-LTF}^{(i_{TS}, i_{LTF})}(t) = \frac{1}{\sqrt{N_{HT-LTF}^{Tone}}} w_{HT-LTF}(t) \quad (36)$$

$$\sum_{k=-N_{SR}}^{N_{SR}} P_{i_{Tx}, (k+i_{L_{TF}}+N_{SR}-u(k)) \% N_{STS}}^{(k)} HTL_k \exp(j2\pi k \Delta_F (t-T_{GI}))$$

$$u(k) = \begin{cases} 1 & k > 0 \\ 0 & k < 0 \end{cases} \quad \text{for 20 MHz} \quad (37)$$

15 and

$$u(k) = \begin{cases} 3 & k > 0 \\ 0 & k < 0 \end{cases} \quad \text{for 40 MHz.} \quad (38)$$

A sequence from 1 – 4 is selected for 20 MHz depending on N_{STS} for the data HT-LTFS. Similarly, a sequence from 5 – 9 is selected for 40MHz. For example with $N_{STS} = 3$ and 20MHz, sequence 3 is selected for the data HT-LTFS.

In the case that $N_{LTF} > N_{STS}$, the extension HT-LTFs are tone interleaved over the extension spatial dimensions. Thus, the extension HT-LTFs are

$$r_{HT-LTF}^{(i_{Tx}, i_{LTF})}(t) = \frac{1}{\sqrt{N_{HT-LTF}^{Tone}}} w_{HT-LTF}(t) \sum_{k=-N_{SR}}^{N_{SR}} P_{i_{Tx}, N_{STS} + (k + (i_{LTF} - N_{STS}) + N_{SR} - u(k)) \% (N_{LTF} - N_{STS})} HTL_k \exp(j2\pi k \Delta_F (t - T_{GI}))$$

for $i_{LTF} = N_{STS}, \dots, N_{LTF} - 1$.

A sequence from 1 – 4 is selected for 20 MHz depending on $N_{LTF} - N_{STS}$ for the extension HT-LTFS. Similarly, a sequence from 5 – 9 is selected for 40MHz. For example with $N_{LTF} - N_{STS} = 2$ and 20MHz, sequence 2 is selected for the extension HT-LTFs.

Since the HT-LTF is tone interleaved across streams, the 56 tones are partitioned across the streams during each OFDM symbol. Tone partitioning into sets for 20MHz is shown in Table 24. At each OFDM symbol interval, each set of tones maps to one space-time steam. And over time, all sets get mapped to a stream.

N_{STS}	Set 0	Set 1	Set 2	Set 3
1	[-28:1:-1] [1:1:+28]			
2	[-28:2:-2] [2:2:28]	[-27:2:-1] [1:2:27]		
3	[-28:3:-1] [2:3:26]	[-27:3:-3] [3:3:27]	[-26:3:-2] [1:3:28]	
4	[-28:4:-4] [1:4:25]	[-27:4:-3] [2:4:26]	[-26:4:-2] [3:4:27]	[-25:4:-2] [4:4:28]

Table 24: Tone partitioning of HT-LTF into sets for 20MHz (56 tones)

Tone partitioning into sets for 40MHz is shown in Table 25.

N_{STS}	Set 0	Set 1	Set 2	Set 3
1	[-58:1:-2] [2:1:+58]			
2	[-58:2:-2] [2:2:+58]	[-57:2:-3] [3:2:57]		

3	[-58:3:-4] [2:3:56]	[-57:3:-3] [3:3:57]	[-56:3:-2] [4:3:58]	
4	[-58:4:-2] [5:4:57]	[-57:4:-5] [2:4:58]	[-56:4:-4] [3:4:55]	[-55:4:-3] [4:4:56]

Table 25: Tone partitioning of HT-LTF into sets for 40MHz (114 tones)

An example of tone interleaving 4 space-time streams across 4 transmit antennas is shown in Figure 35.

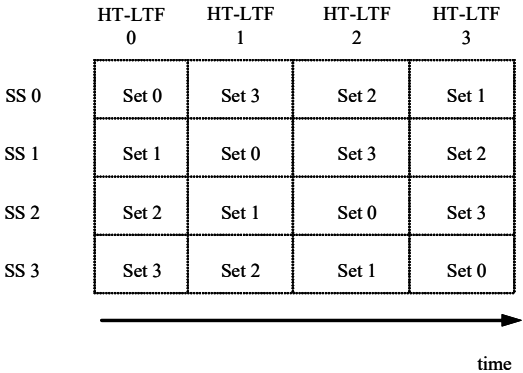


Figure 35: HT-LTF tone interleaving across 4 spatial streams

An example of tone interleaving with 2 space-time streams and 2 extension HT-LTFs is shown in Figure 36.

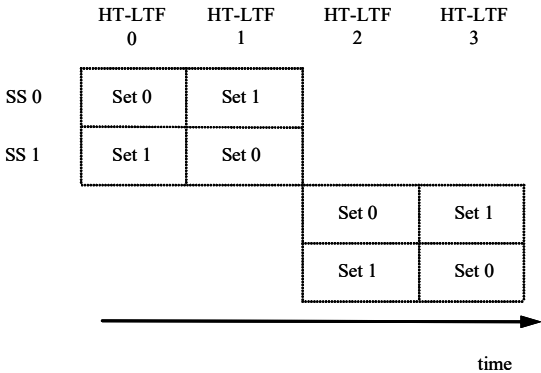


Figure 36: HT-LTF tone interleaving of 2 spatial streams with 2 extension HT-LTFs across 4 transmit antennas

11.2.1.6 Signal fields specification

The L-LTF shall be followed by the signal fields L-SIG and HT-SIG. The coding and modulation follow the steps of clause 17.3.4 in ref[2]: BPSK modulation is used for the L-SIG and HT-SIG, with code rate $\frac{1}{2}$ resulting in 6 Mbit/s. Between the LSIG and the HT-SIG symbol, the BPSK modulation shall be rotated counter-clockwise by 90 degrees. This phase rotation can be used to “auto-detect” whether the frame being received is legacy or HT. The constellation bit encoding is depicted in Figure 37.

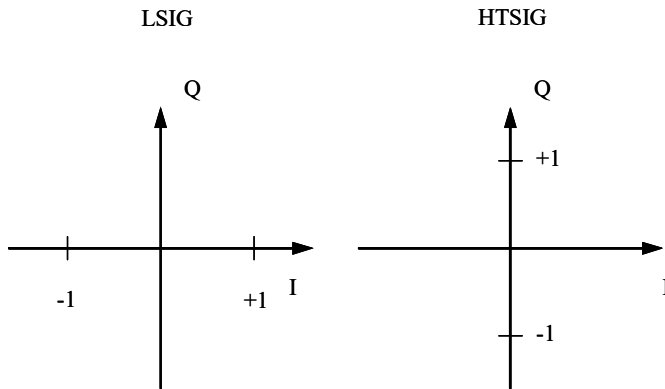


Figure 37: Constellation specification for LSIG and HTSIG

11.2.1.6.1 L-SIG

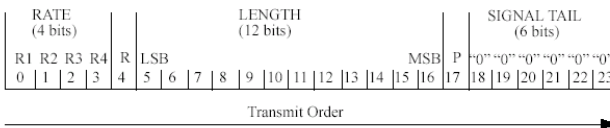


Figure 38: SIGNAL field bit assignment

In the 20MHz mode, the format of the LSIG field shall be the same as the SIGNAL field as defined in figure 111 in 17.3.4 in [1]. The combination of RATE and LENGTH is used to signal a station (OFDM mode only) the duration of a HT transmission. This duration does not have to be the actual duration of the HT frame. It can be used to reserve the medium beyond the actual transmission. The reservation of the medium through this kind of signalling is called Extended PHY protection.

To prevent a legacy station from accessing the medium during a HT frame transmission, the “duration” calculated from the RATE and LENGTH fields shall be at least as large as the actual duration of the HT frame, which is measured from the end of the L-SIG field to the end of the DATA field. During an HT transmission, the RATE field is set to 6Mbps, whereas the LENGTH field is set based on the “duration” value.

In the 40MHz mode, the legacy signal field is duplicated such that tones are filled from -58 to -6 (lower-subchannel), and from +6 to +58 (upper-subchannel). The upper subchannel shall be phase rotated by 90 degrees, in the same way as the LTS as described in 11.2.1.5.2

The LSIG shall be transmitted in the same fashion as the legacy short and the legacy long training fields. If L-STF and L-LTF are transmitted from a single antenna, we index that antenna as $i_{Tx} = 1$ to be consistent with 11.2.1.5.2. Denote $LSIG_{-26,26}$ and $LSIG_{-58,58}$ as the LSIG OFDM symbol generated for 20 MHz and 40 MHz respectively.

The L-SIG waveform is

$$r_{L-SIG}^{i_{Tx}}(t) = \frac{1}{\sqrt{N_{L-SIG}^{Tone}}} w_{L-SIG}(t) \sum_{k=-N_{SR}}^{N_{SR}} p_{i_{Tx}}^{L(k)} LSIG_k \exp(j2\pi k \Delta_F (t - T_{GI})) \quad (40)$$

11.2.1.6.1.1 Data rate (RATE)

For a legacy station (11a or 11g), RATE has the original meaning as is defined in Table 80 of section 17.3.4.1 in [1]. For reference the table is repeated here:

Rate (Mbits/s)	R1-R4
6	1101
9	1111
12	0101
18	0111
24	1001
36	1011
48	0001
54	0011

Table 26: Content of the legacy SIGNAL field

11.2.1.6.1.2 PLCP length field (LENGTH)

The PLCP length field in HT is used to indicate to both legacy and HT stations a protection duration. It contains a value, which when combined with the rate field defines a duration. The number of bytes in the LENGTH field is calculated based on the perceived RATE of a legacy station defined in R1-R4 and the actual number of bytes that the MAC is currently requesting the PHY to transmit, taking into account the number of transmit antennas (spatial streams), the bandwidth and the extra fields (symbols) in the preamble.

As indicated in 11.2.1.6.1, the calculated duration is allowed to be longer than the actual duration of the HT transmission. However the LENGTH value should be equal to or smaller than 2346 bytes to avoid mis-interpretation by existing legacy devices.

11.2.1.6.2 HT-SIG

The L-SIG field shall be followed by the HT-SIG, which serves as the signal field for the HT PHY. HT-SIG consists of two OFDM symbols: HT-SIG1 and HT-SIG2. HT-SIG1 shall be transmitted first in time.

The encoding of HT-SIG-1 and HT-SIG-2 shall be the same as L-SIG, with the exception that the BPSK modulation is rotated 90 degrees as described in clause 11.2.1.6.

In the 40MHz mode, the HT-SIG-1 and HT-SIG-2 are duplicated. The upper sub-channel shall be phase rotated by 90 degrees in the same way as the L-LTF, as described in 11.2.1.5.2

Error! Reference source not found. shows the bit assignment for the two symbols. They will be described in the next clauses.

HT-SIG-1 and HT-SIG-2 shall be transmitted in a similar fashion as the LSIG. Denote $HTSIG_{-26,26}^0$ and $HTSIG_{-58,58}^1$ as the first and second OFDM symbol of the following defined HT-SIG as a data field. Then

$$r_{HT-SIG}^{(t_r)}(t) = \frac{1}{\sqrt{N_{HT-SIG}^{Tone}}} \sum_{n=0}^1 w_{Symbol}(t - nT_{Symbol}) \sum_{k=-N_{SR}}^{N_{SR}} p_{t_{rx}}^{L(k)} HTSIG_k^n \exp(j2\pi k \Delta_F (t - T_{GI} - nT_{Symbol})) \quad (41)$$

where $T_{Symbol} = 4 \mu \text{ sec}$ is the OFDM symbol duration.

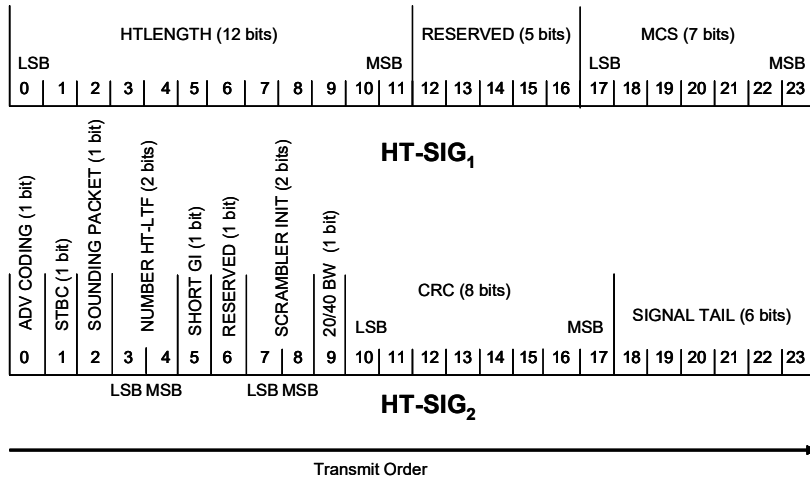


Figure 39: HT-SIG field bit assignments

11.2.1.6.2.1 HTLENGTH field

The HTLENGTH field shall be an unsigned 12-bit integer, which is interpreted using the following table:

HTLENGTH	Contains A-MPDU?	Length interpretation
b'H ₁₁ H ₁₀ H ₉ H ₈ H ₇ H ₆ H ₅ H ₄ H ₃ H ₂ H ₁ H ₀		
b'00_ H ₉ H ₈ H ₇ H ₆ H ₅ H ₄ H ₃ H ₂ H ₁ H ₀	No	b'00_ H ₉ H ₈ H ₇ H ₆ H ₅ H ₄ H ₃ H ₂ H ₁ H ₀ octets
b'01_ H ₉ H ₈ H ₇ H ₆ H ₅ H ₄ H ₃ H ₂ H ₁ H ₀	No	b'01_ H ₉ H ₈ H ₇ H ₆ H ₅ H ₄ H ₃ H ₂ H ₁ H ₀ octets
b'10_ H ₉ H ₈ H ₇ H ₆ H ₅ H ₄ H ₃ H ₂ H ₁ H ₀	No	b'10_ H ₉ H ₈ H ₇ H ₆ H ₅ H ₄ H ₃ H ₂ H ₁ H ₀ octets
b'11_ H ₉ H ₈ H ₇ H ₆ H ₅ H ₄ H ₃ H ₂ H ₁ H ₀	Yes	b'H ₉ H ₈ H ₇ H ₆ H ₅ H ₄ H ₃ H ₂ H ₁ H ₀ OFDM symbols

Table 27: Interpretation of HT-LENGTH field in HT-SIG

Bit 0 (i.e. H₀) is the LSB (least significant bit) and shall be transmitted first in time to the channel encoder.

11.2.1.6.2.2 MCS field

The MCS field is a 7-bit field (bit 17-23 of HT-SIG1) that defines the modulation and coding scheme, as indicated in Table 17. MCS indices from 0 to 15 are mandatory, and the rest are optional.

11.2.1.6.2.3 ADVCODING

ADVCODING is a 1-bit field that indicates if advanced coding has been applied to the PPDU.

11.2.1.6.2.4 STBC

This bit is set to 1 if the PPDU has been encoded using STBC, else it is set to NULL.

11.2.1.6.2.5 SOUNDING PACKET

This bit indicates that a sounding PPDU is being sent. The reception of a PPDU with the sounding bit set to '1' indicates to an STA that it should buffer the CSI estimate if it has the capability and desire to do so, as the contents of the MPDU will request a function requiring further processing of the CSI. A sounding packet may contain any valid number of HT-LTFs ($N_{STS} \leq N_{LTF} \leq N_{TX}$).

11.2.1.6.2.6 NUMBER (of) HT-LTF

These bits indicate the number of HT-LTFs in the current PPDU. The number of HT-LTFs may be greater than the number of space-time-streams. Note that the number of HT-LTFs is less than or equal to the number of transmit antennas. The N_LTF bits are encoded as shown in Table 28:

HT-SIG encoding of N_LTF	Enumeration of N_LTF
b'00	1
b'01	2
b'10	3
b'11	4

Table 28: Encoding of N_LTF in HT-SIG

11.2.1.6.2.7 SHORT GI (Optional)

SHORT GI is a 1-bit field. If SHORT GI is 1, the Short Guard Interval is used in the data portion of the frame.

11.2.1.6.2.8 SCRAMBLERINIT

SCRAMBLERINIT is a 2-bit field that contains the initialization value of the scrambler. This value is used to initialize the scrambler at the receiver. The mapping of the 2-bit field to initialization sequences is described in Table 11.

1 **11.2.1.6.2.9 20/40 BW**

2 This bit indicates whether the current PPDU is signaled in 20MHz or 40MHz bandwidth. A
3 value of 0 indicates 20MHz, whereas a value of 1 indicates 40MHz.

5 **11.2.1.6.2.10 CRC**

6 The CRC field is an 8-bit CRC value. It is used as a Frame Check Sequence (FCS) to protect the
7 information-bearing fields of LSIG, HT-SIG1 and HT-SIG2.

8
9 The CRC field shall be the one's complement of the remainder generated by the modulo 2
10 division of the protected bits by the polynomial

11
$$x^8 + x^2 + x^1 + 1 \qquad (42)$$

12
13 where the shift-register state shall be preset to all-ones. The protected bits shall be bit0-bit16 of
14 LSIG, bit0-bit23 of HTSIG1, and bit0-bit9 of HTSIG2. The protected bits shall be processed by
15 the CRC encoder in transmit order. A schematic of the processing is shown in Figure 40.

16
17 As an example, given the following LSIG, HT-SIG1 and HT-SIG2 fields

18 1101 0001 1101 1101 0000 0000 [LSIG]
19 0111 1011 0100 1011 1010 0000 [HT-SIG1]
20 0010 1101 10CC CCCC CC00 0000 [HT-SIG2]
21 b0.....b23 [leftmost bit (b0) transmitted first in time]

22
23 then the protected bits input to the CRC encoder are

24 1101 0001 1101 1101 0, 0111 1011 0100 1011 1010 0000, 0010 1101 10

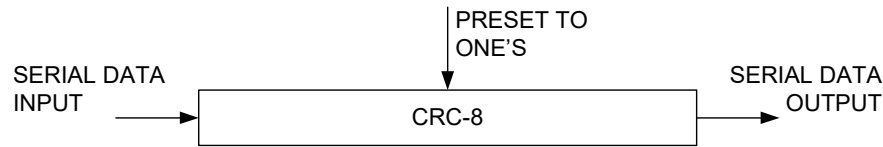
25
26 and the calculated CRC8 equals

27 00001101

28
29 so that HT-SIG2 equals

30 0010 1101 1000 0011 0100 0000

31



1. Present shift register to all one's
2. Shift bit0-bit16 of LSIG, HTSIG1, and bit0-bit9 of HTSIG2 through the shift register
3. Take one's complement of the remainder
4. Transmit out serial x^7 first

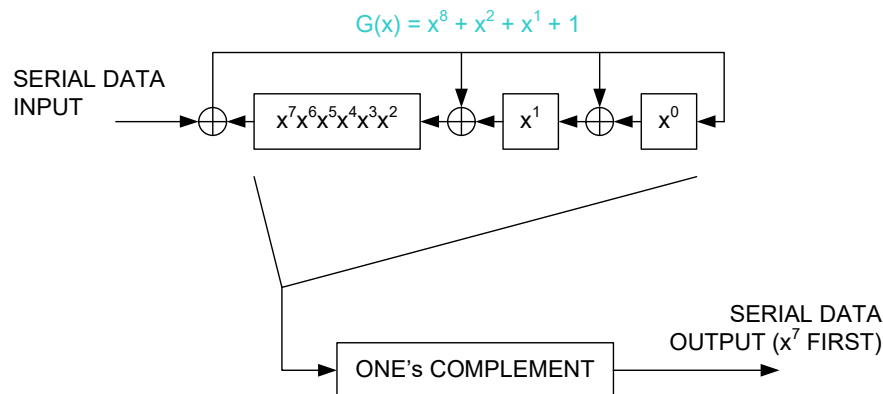


Figure 40: CRC8 implementation

11.2.1.6.2.11 SIGNALTAIL

The bits 18-23 constitute the SIGNALTAIL field, and all 6 bits shall be set to zero.

11.2.1.7 Datafield

Contrary to 801.11a, the data field in our proposal does not contain a SERVICE field.

The data field contains the PSDU, the Tail bits and the PAD bits. All bits in the DATA field are scrambled, as described in 11.2.1.7.3. The PPDU is de-multiplexed across several spatial streams, which are created after the parser.

11.2.1.7.1 PSDU tail bit field (TAIL)

The PSDU tail bit field shall be six bits of "0," which are required to return the convolutional encoder to the "zero state." This procedure improves the error probability of the convolutional decoder, which relies on future bits when decoding and which may be not be available past the

1 end of the message. The PLCP tail bit field shall be produced by replacing six scrambled “zero”
2 bits following the message end or padding bit(s) with six non-scrambled “zero” bits.
3 When A-MPDU is not applied, tail bits should be located just after PSDU, as same as in 802.11a.
4 When A-MPDU is applied, tail bits should be located after padding bit(s) such that the tail bits
5 always appear as the last 6 bits in the last OFDM symbol.

6 **11.2.1.7.2 Pad bits (PAD)**

7 The length of the message is extended so that it becomes a multiple of the number of data bits
8 per OFDM symbol for each data (spatial) stream. The number of pad bits is dependent on how
9 the bits are divided over the spatial streams.
10 When A-MPDU is not applied, pad bit(s) should be located after tail bits as same as in 802.11a,
11 if padding is required. In this case, receiver PHY should remove pad bit(s) and tail bits before
12 delivering decoded bits to MAC layer.
13 When A-MPDU is applied, pad bit(s) should be located between PSDU and tail bits such that the
14 tail bits always appear as the last 6 bits in the last OFDM symbol. In this case, receiver PHY
15 should deliver all decoded bits, except for tail bits, to MAC layer.

16 **11.2.1.7.3 PLCP Data Scrambler and Descrambler**

17 The 11a Scrambler and Descrambler will be used as described in 17.3.5.4 in ref [1].
18 The DATA field, composed of PSDU, tail, and pad parts, shall be scrambled with the length-127
19 frame-synchronous scrambler.
20 The scrambler shall be initialized according to the SCRAMBLERINIT fields in HT-SIG2.
21 As described in 11.2.1.7.1 the PLCP tail bit field shall be produced by replacing six scrambled
22 “zero” bits following the message end with six nonscrambled “zero” bits.
23

24 **11.2.1.7.4 Antenna streams / Transmitter architecture**

25 In the basic MIMO mode, space-time streams may be mapped to transmit antennas using direct
26 mapping (Figure 21), or spatial spreading (Figure 22). In the case of direct mapping, the number
27 of space-time streams equals the number of active transmit antennas. By active, we imply those
28 antennas that transmit data fields. In the case of spatial spreading, the number of space-time
29 streams must be less than or equal to the number of transmit antennas.
30
31 The information bits first go through a convolutional encoder. The convolutional encoder is of
32 rate $\frac{1}{2}$, from which other rates are derived by puncturing (see 11.2.1.7.6). The output of the
33 puncturer feeds into the spatial parser, which creates several spatial streams, using round robin
34 cycling. The frequency interleaver places the bits in the frequency domain and the constellation
35 position according to the rules of the 802.11a interleaver. The interleaved bits are then mapped to
36 constellation points. The resulting QAM symbols are fed to the antenna map transformation
37 (Figure 20), and the output of this for each transmit antenna is fed as a block of data to the iFFT
38 to create the time-domain signal. The pilot tones are also inserted in the frequency domain. The
39 cyclical prefix is inserted in the time domain, and windowing of the OFDM symbols is also
40 performed in the time domain. The resulting signal is then converted into analog format via a
41 Digital-to-Analog (D/A) converter.

42 **11.2.1.7.5 Encoder**

43 The DATA field shall be coded with the convolutional encoder of coding rate $R=1/2$. The
44 encoder is defined in clause 17.3.5.5 in [1] (i.e. the 11a encoder).

11.2.1.7.6 Puncturing of Coded Data

Coded bits at the output of the convolutional encoder are at rate 1/2. For lower rates, the puncturer can selectively puncture the coded bits to achieve the desired “effective” coding rate of 2/3, 3/4 or 5/6. For code rates of 2/3 and 3/4 the puncturing patterns are as defined in clause 17.3.5.5 in [1]. For a code rate of 5/6, the puncturing pattern is illustrated in Figure 41.

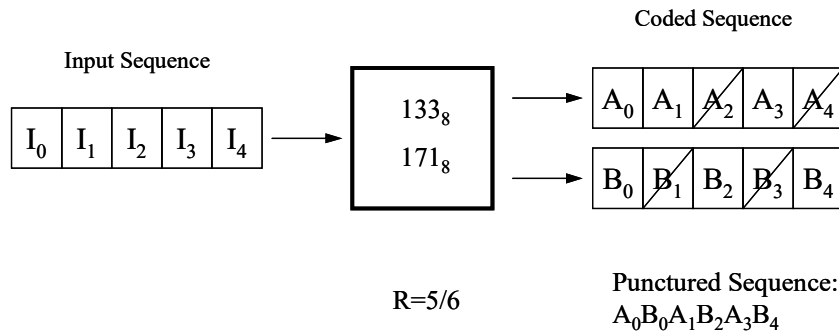


Figure 41: Puncturing pattern for code rate = 5/6

In the basic MIMO mode, all spatial streams are identically punctured.

11.2.1.7.7 Data interleaving

Coded and punctured bits are interleaved across spatial streams and frequency tones. There are two steps to the space-frequency interleaving: spatial stream parsing and frequency interleaving.

11.2.1.7.7.1 Spatial Parsing

Encoded and punctured bits are parsed to multiple spatial streams by a round-robin parser. Define:

$$s = \max \{N_{BPSC} / 2, 1\} \quad (43)$$

which is the number of QAM bit order values. The parser sends consecutive blocks of s bits to each spatial streams in a round-robin fashion starting with the first spatial stream. The reason for parsing in blocks of s bits is to prevent clustering of QAM orders.

11.2.1.7.7.2 Frequency interleaver

All encoded bits shall be interleaved by a separate block interleaver for each spatial stream, with a block size corresponding to the number of coded bits in a single OFDM symbol, N_{CBPS} . The block interleavers are based on the 802.11a interleaver, with certain modifications to allow for multiple spatial streams and 40MHz transmissions as shown in Figure 42.

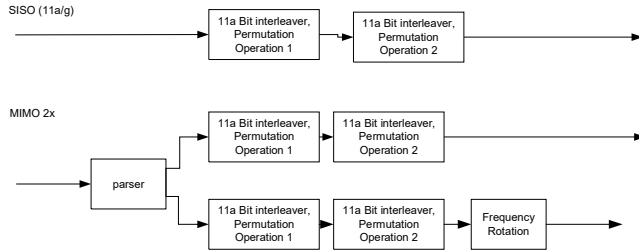


Figure 42: Structure of interleaver

The interleaver is defined by a three-step permutation. The first permutation ensures that adjacent coded bits are mapped onto nonadjacent subcarriers. The second permutation ensures that coded bits are mapped alternately onto less and more significant bits of the constellation and thereby long runs of low reliability (LSB) bits are avoided. The third permutation ensures that coded bits are mapped to achieve better frequency-spatial diversity among all spatial streams via frequency rotation. The operations of the first two permutations are the same as in 802.11a.

The basic interleaver array has N_{row} rows and N_{column} columns and the base of frequency rotation is defined by N_{rot} . These parameters are specified in Table 29 where N_{BPSC} is the number of coded bits per subcarrier (e.g., $N_{BPSC} = 1$ for BPSK, 2 for QPSK, 4 for 16 QAM, etc).

Table 29: Interleaver Parameters

	N_{column}	N_{row}	N_{rot}
20 MHz channels	13	$4N_{BPSC}$	11
40 MHz channels	18	$6 N_{BPSC}$	29

The amount of frequency rotation for each spatial streams is illustrated in Table 30.

Table 30: Frequency Rotation across spatial streams

Frequency Rotation	Total Number of Streams			
	1	2	3	4
1 st stream	0	0	0	0
2 nd stream		$2N_{rot}$	$2N_{rot}$	$2N_{rot}$
3 rd stream			N_{rot}	N_{rot}
4 th stream				$3N_{rot}$

The index of the coded bit before the first permutation shall be denoted by k ; i shall be the index after the first and before the second permutation; j shall be the index after the second permutation and before the third permutation; r shall be the index after the third permutation and just prior to modulation mapping.

The first permutation is defined by the rule

$$i = N_{row} \times (k \bmod N_{column}) + \text{floor}(k / N_{column}) \quad k = 0, 1, \dots, N_{CBPS} - 1 \quad (44)$$

The second permutation is defined by the rule

$$j = s \times \text{floor}(i / s) + (i + N_{CBPS} - \text{floor}(N_{column} \times i / N_{CBPS})) \bmod s \quad i = 0, 1, \dots, N_{CBPS} - 1 \quad (45)$$

where s is determined according to

$$s = \max(N_{BPSC} / 2, 1) \quad (46)$$

The third permutation is defined by the rule

$$r = (j - ((2 \times i_{ss}) \bmod 3 + 3 \times \text{floor}(i_{ss} / 3)) \times N_{rot} \times N_{BPSC}) \bmod N_{CBPS} \quad j = 0, 1, \dots, N_{CBPS} - 1 \quad (47)$$

where $i_{ss} = 0, 1, \dots, N_{ss} - 1$ is the index of the spatial stream on which this interleaver is operating.

The deinterleaver, which performs the inverse relation, is also defined by three permutations.

Here the index of the original received bit before the first permutation shall be denoted by r ; j shall be the index after the first and before the second permutation; i shall be the index after the second and before the third permutation; and k shall be the index after the third permutation.

The first permutation is defined by the rule

$$j = (r + ((2 \times i_{ss}) \bmod 3 + 3 \times \text{floor}(i_{ss} / 3)) \times N_{rot} \times N_{BPSC}) \bmod N_{CBPS}, \quad r = 0, 1, \dots, N_{CBPS} - 1 \quad (48)$$

This permutation is the inverse of the permutation described in Equation (44).

The second permutation is defined by the rule

$$i = s \times \text{floor}(j/s) + (j + \text{floor}(N_{\text{column}} \times j / N_{\text{CBPS}})) \bmod s, \quad j = 0, 1, \dots, N_{\text{CBPS}} - 1 \quad (49)$$

where s is as defined in Equation (46). This permutation is the inverse of the permutation described in Equation (45).

The third permutation is defined by the rule

$$k = N_{\text{column}} \times i - (N_{\text{CBPS}} - 1) \text{floor}(i / N_{\text{row}}), \quad i = 0, 1, \dots, N_{\text{CBPS}} - 1 \quad (50)$$

This permutation is the inverse of the permutation described in Equation (47).

11.2.1.7.8 Subcarrier Modulation Mapping

The subcarrier modulation mapping for BPSK, QPSK, 16-QAM, and 64-QAM will be identical to clause 17.3.5.7 in [1]

There is one exception as described in clause 11.2.1.6. The mapping of the HT-SIG field shall be rotated by 90 degrees.

11.2.1.7.8.1 Subcarrier Modulation Mapping for 256-QAM (optional)

256QAM is introduced in the optional MCS sets in MCS capability classes of "1000", "1101", "1110", and "1111".. The normalization factor K_{MOD} for 256QAM is $1/\sqrt{170}$. For 256-QAM, $b_0b_1b_2b_3$ determines the I value and $b_4b_5b_6b_7$ determines the Q value. The constellation mapping for 256QAM is as follows.

Table 31: Constellation Mapping for 256-QAM

Input bits $b_0b_1b_2b_3$	I-out	Input bits $b_4b_5b_6b_7$	Q-out
0000	-15	0000	-15
0001	-13	0001	-13
0011	-11	0011	-11
0010	-9	0010	-9
0110	-7	0110	-7
0111	-5	0111	-5
0101	-3	0101	-3
0100	-1	0100	-1
1100	1	1100	1
1101	3	1101	3
1111	5	1111	5
1110	7	1110	7
1010	9	1010	9
1011	11	1011	11
1001	13	1001	13
1000	15	1000	15

11.2.1.7.9 MIMO-OFDM symbol iFFT mapping

For the MIMO-OFDM operation in 20 MHz bandwidth, each OFDM symbol is constructed from 56 tones, of which 52 are data tones and 4 are pilot tones. The tone mapping is identical to that in IEEE 802.11a (subclause 17.3.5.9 in reference) except the 2 extra tones on either side.

Construction of the OFDM data symbol in 40MHz begins with bonding two adjacent 20MHz OFDM symbols, as shown in Figure 43. There are a total of 11 guard tones between the two 20MHz channels, ranging from -5 to +5. Note that the legacy channels occupy tones from -58 to -6 in the lower sub-channel, and from +6 to +58 in the upper sub-channel. Of the 11 guard tones, 3 are nulled out: -1, 0, +1. This provides 8 additional data tones. Two DC tones are also inherited from the legacy sub-channels. These occur at -32 and +32 in the lower and upper sub-channels respectively. There are 4 pilot tones in each legacy sub-channel, and when mapped to the 40MHz iFFT indices, they occur at $\pm 53, \pm 39, \pm 25, \pm 11$. Of these 8 tones, the two tones at -39 and +39 are swapped with data, leading to a total of 6 pilot tones in the 40MHz channel. Tone assigned during 40MHz for DATA symbols can be summarized as:

$$\text{Nulled Tones} = \{-64 \dots -59, -1, 0, +1, +59 \dots +63\}$$

$$\text{Populated Tones} = \{-58 \dots -2, +2 \dots +58\}$$

$$\text{Pilot Tones} = \{-53, -25, -11, +11, +25, +53\}$$

$$\text{Data Tones} = \{\text{Populated Tones}\} - \{\text{Pilot Tones}\}$$

(51)

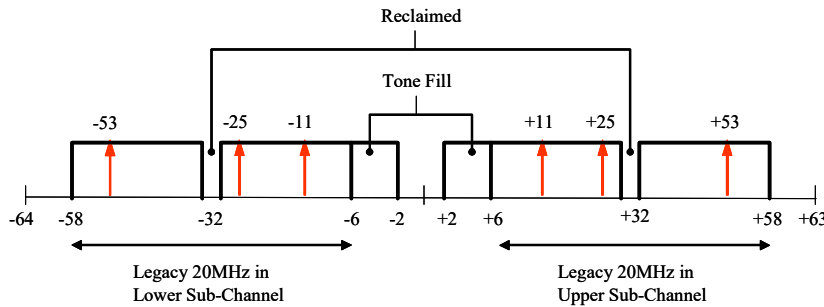


Figure 43: Tone Format for 40MHz channelization

The mapping of the input of the 40MHz channel to a 128-point IFFT is illustrated in Figure 44.

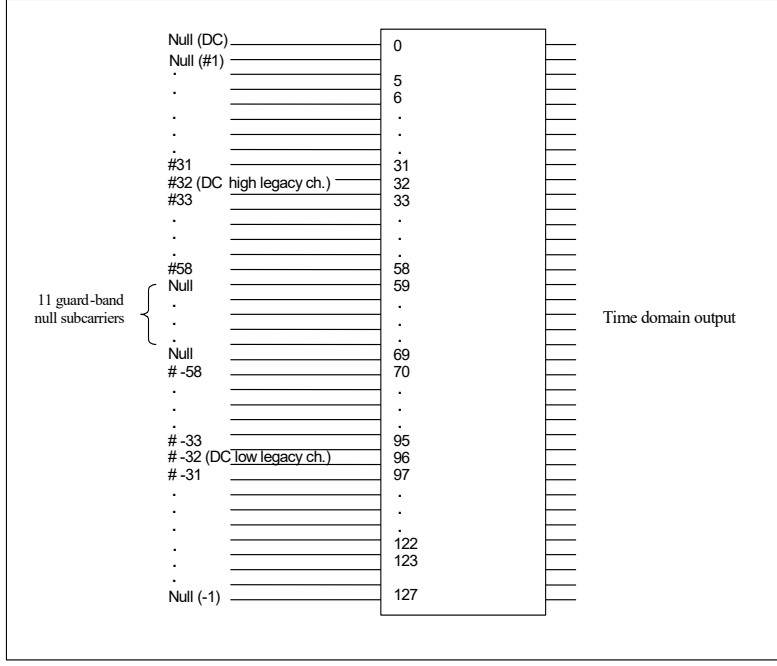


Figure 44 Inputs and Outputs of IFFT for a 40 MHz channel

The complex numbers after the mapping are divided into groups of N_{SD} , where $N_{SD} = 52$ in the 20MHz mode and $N_{SD} = 108$ in the 40MHz mode (excluding 6 Mbps duplicate format).

Following the convention in clause 17.3.5.9 in [1], the complex number is denoted as $d_{k,n}^{(i_{SS})}$, which corresponds to the k th modulation symbol in the n th OFDM symbol that is transmitted on space-time stream i_{STS} ($= 0, \dots, N_{STS} - 1$).

The complete data field is

$$r_{HT-Data}^{(i_{Tx})}(t) = \sum_{n=0}^{N_{Data}-1} r_{HT-Data,n}^{(i_{Tx})}(t - nT_{Symb}). \quad (52)$$

The n^{th} OFDM data symbol is

$$r_{HT-Data,n}^{i_{TX}}(t) = w_{Symb}(t) \left\{ \sum_{k=0}^{N_{SD}-1} \left(\sum_{i_{STS}=0}^{N_{STS}-1} p_{i_{TX},i_{STS}}^{(k)} d_{i_{STS}}^{(k,n)} \right) \exp(j2\pi M(k) \Delta_F (t - T_{GI})) \right. \\ \left. + p_{t_{n+3}} \sum_{k=-N_{SR}}^{N_{SR}} \left(\sum_{i_{STS}=0}^{N_{STS}-1} p_{i_{TX},i_{STS}}^{(k)} PT_{i_{STS}}^{(k,n)} \right) \exp(j2\pi k \Delta_F (t - T_{GI})) \right\} \quad (53)$$

where function $M(k)$, defines the mapping from the logical subcarrier number k to a value between $-N_{SR}$ and $+N_{SR}$, while skipping the pilot subcarriers and DC and its adjacent subcarriers. $M(k)$ in the 20MHz mode is same as the one defined in clause 17.3.5.9 in [1]. $M(k)$ in the 40MHz mode is defined as

$$M(k) = \begin{cases} k-58 & 0 \leq k \leq 4 \\ k-57 & 5 \leq k \leq 31 \\ k-56 & 32 \leq k \leq 44 \\ k-55 & 45 \leq k \leq 53 \\ k-52 & 54 \leq k \leq 62 \\ k-51 & 63 \leq k \leq 75 \\ k-50 & 76 \leq k \leq 102 \\ k-49 & 103 \leq k \leq 107 \end{cases} \quad (54)$$

The contribution of pilot subcarriers in the 20MHz mode is given by (24) in clause 17.3.5.9 in ref [1]. The subcarrier frequency locations in the 20MHz mode is shown in Figure 117 in clause 17.3.5.9 in ref [1]. The subcarrier frequency locations in the 40MHz mode is shown in Figure 43.

The iFFT mapping for the 6Mbps duplicate mode in 40MHz differs from the mapping shown in (53):

$$r_{HT-Data,n}^{i_{TX}}(t) = w_{Symb}(t) \left\{ \sum_{k=0}^{N_{SD}-1} \left(\sum_{i_{STS}=0}^{N_{STS}-1} p_{i_{TX},i_{STS}}^{(k)} d_{i_{STS}}^{(k,n)} \right) \left(\exp(j2\pi (M(k)-32) \Delta_F (t - T_{GI})) \right. \right. \\ \left. \left. + j \exp(j2\pi (M(k)+32) \Delta_F (t - T_{GI})) \right) \right. \\ \left. + p_{t_{n+3}} \sum_{k=-N_{SR}}^{N_{SR}} \left(\sum_{i_{STS}=0}^{N_{STS}-1} p_{i_{TX},i_{STS}}^{(k)} PT_{i_{STS}}^{(k,n)} \right) \left(\exp(j2\pi (k-32) \Delta_F (t - T_{GI})) \right. \right. \\ \left. \left. + j \exp(j2\pi (k+32) \Delta_F (t - T_{GI})) \right) \right\} \quad (55)$$

1 where, $N_{SD} = 52$ and $N_{SR} = 28$ are values that correspond to a 20 MHz transmission. $M(k)$,
2 $PT_{i_{STS}}^{(k)}$ and pt_n follow the definitions in (23) to (25) in clause 17.3.5.9 in [ref 2]. $PT_{i_{STS}}^{(k)}$ for the
3 HT 40MHz mode is defined in 11.2.1.7.10.2.

5 11.2.1.7.10 Pilot subcarrier

6 In each OFDM symbol, four of the subcarriers in 20 MHz mode and six of the subcarriers in 40
7 MHz mode are dedicated to pilot signals in order to make the coherent detection robust against
8 frequency offsets and phase noise. These pilot signals shall be put in subcarriers -21, -7, 7, and
9 21 in 20MHz mode, and in subcarriers -53, -25, -11, 11, 25 and 53 in 40MHz mode.

11.2.1.7.10.1 Legacy pilot subcarriers

12 Legacy pilots are defined as in 802.11a; refer to clause 17.3.5.8 in [1].

14 11.2.1.7.10.2 Pilot subcarriers in HT mode

15 The contribution of pilot subcarriers at the i_{Tx} th transmission stream in 20MHz mode is produced
16 by inverse Fourier transform of sequence $PT_{k,\eta}^{(i_{Tx})}$ given by

$$PT_{i_{STS}}^{(-28..28,n)} = \{0,0,0,0,0,0,0, PT_{i_{STS}}^{(-21,n)}, 0,0,0,0,0,0,0,0,0,0, PT_{i_{STS}}^{(-7,n)}, 0,0,0,0,0,0, \\ 0,0,0,0,0,0, PT_{i_{STS}}^{(-7,n)}, 0,0,0,0,0,0,0,0,0,0,-PT_{i_{STS}}^{(21,n)}, 0,0,0,0,0,0\} \quad (56)$$

18 where non-zero element of $PT_{i_{\text{Tx}}}^{(k,n)}$ is generated by the following rule

$$19 \quad PT_{i_{STS}}^{(k,n)} = \exp\left\{\frac{j\pi}{2}(i_{SS}-1)m\right\}, \quad m = \left(\frac{1}{2}\left(\frac{k}{7}+3\right)+n\right) \bmod 4 \quad (57)$$

20 In the 40MHz mode, $PT_{k,n}^{(i_{Tx})}$ is given by

$$\begin{aligned}
PT_{i_{STS}}^{(-58,.58,n)} = & \{0,0,0,0,0,PT_{i_{STS}}^{(-53,n)},0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,PT_{i_{STS}}^{(-25,n)},0,0, \\
& 0,0,0,0,0,0,0,0,0,0,-PT_{i_{STS}}^{(-11,n)},0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,PT_{i_{STS}}^{(11,n)},0,0,0,0, \\
& 0,0,0,0,0,0,0,0,0,-PT_{i_{STS}}^{(25,n)},0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0, \\
& 0,0,PT_{i_{STS}}^{(53,n)},0,0,0,0,0\}
\end{aligned}
\tag{58}$$

22 where non-zero element of $PT_{k,n}^{(i_{rx})}$ is generated by the following rule

$$23 \quad PT_{I_{STS}}^{(k,n)} = \exp\left\{\frac{j\pi}{2}(i_{STS}-1)m\right\}, \quad m = \begin{cases} \left(\frac{(k+11)}{14}+3+n\right) \bmod 4, & k = -53, -25, -11 \\ \left(\frac{(k+3)}{14}+3+n\right) \bmod 4, & k = 11, 25, 53 \end{cases} \quad (59)$$

The polarity of the pilot subcarriers is controlled by sequence pt_n , which is a cyclic extension of the 127 elements sequence as defined in clause 17.3.5.9 in ref[2].

11.2.1.7.11 GI / windowing

The windowing function in both 20MHz and 40MHz modes is the same as the one described in clause 17.3.2.4 and 17.3.2.5 in [1]. The example in clause 17.3.2.5 in [1] still holds for the 20MHz modes. In the 40MHz modes, the changes in this example is the sampling rate becomes 40MHz and $T_{TR} = 50ns$, then the discrete implementation of the windowing function is

$$w_r[n] = w_r(nT_s) = \begin{cases} 1 & 1 \leq n \leq 159 \\ 0.5 & 0,160 \\ 0 & otherwise \end{cases} \quad (60)$$

11.2.1.8 Clear channel assessment

When operating in the 5 GHz band the HT PHY shall follow the CCA requirements of 11a, clause 17.3.10.5 in [1]. When operating in the 2.4 GHz band the HT PHY shall follow the 11g spec according to 19.3.5 and 19.4.6 in ref [3].

11.2.1.9 PMD operating spec

In the 20 MHz bandwidth mode the HT PHY shall follow the 11a spec (clause 17.3.8 in ref [1]) and subsequent specifications when operating in the 5 GHz band.
In the 20 MHz bandwidth mode the HT PHY shall follow the 11g spec (clause 19.4) when operating in the 2.4 MHz band.

11.2.1.9.1 Transmit spectral mask

11.2.1.9.1.1 20MHz channel spacing

In the 20 MHz bandwidth mode the HT PHY shall follow 17.3.9.2 in ref [1]. The transmitted spectrum shall have a 0dBm (dB relative to the maximum spectral density of the signal) bandwidth not exceeding 18MHz, -20dBm at 11 MHz frequency offset, -28dBm at 20MHz frequency offset and -45dBm at 30MHz frequency offset and above. The transmitted spectral density of the transmitted signal shall fall within the spectral mask, as shown in Figure 1. The measurements shall be made using a 100kHz resolution bandwidth and a 30kHz video bandwidth.

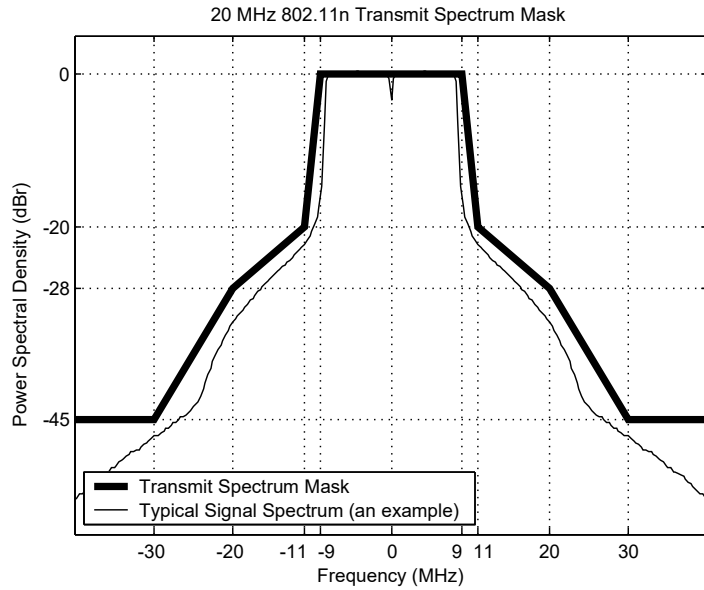


Figure 45: Transmit Spectrum Mask for 20MHz channelization

11.2.1.9.1.2 40MHz channel spacing

The transmitted spectrum shall have a 0dBm (dB relative to the maximum spectral density of the signal) bandwidth not exceeding 38MHz, -20dBm at 21 MHz frequency offset, and -45dBm at 60MHz frequency offset and above. The transmitted spectral density of the transmitted signal shall fall within the spectral mask, as shown in Figure 2. The measurements shall be made using a 100kHz resolution bandwidth and a 30kHz video bandwidth.

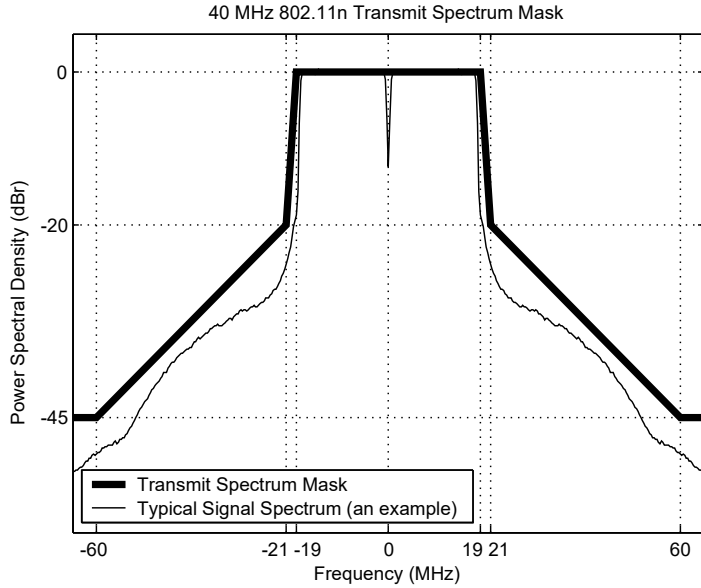


Figure 46: Transmit spectrum mask for 40MHz channelization

A HT device transmitting a 20MHz signal in a 40MHz BSS shall conform to the spectral mask shown in Figure 46.

11.2.2 Space Time Block Coding (Optional Mode)

11.2.2.1 STBC PPDU format

The STBC PPDU format is identical to the Basic MIMO PPDU format (see section 11.2.1.1), with the added requirement that the DATA fields contain an even number of OFDM symbols.

11.2.2.2 Space Time Block Coding of Modulation Symbols

When STBC encodes a single input stream of modulation symbols, the input modulation symbol in subcarrier ℓ in OFDM symbol n is $s_\ell(n)$. For each sequential pair of input symbols in the input modulation symbol stream, the STBC processing generates two output symbol vectors as follows. Given two sequential input symbols $s_\ell(2k)$ and $s_\ell(2k+1)$, the STBC processing generates two sequential output symbol vectors $\mathbf{x}_\ell(2k)$ and $\mathbf{x}_\ell(2k+1)$ given by

$$\mathbf{x}_\ell(2k) = \begin{bmatrix} s_\ell(2k) \\ -s_\ell^*(2k+1) \end{bmatrix} \quad \text{and} \quad \mathbf{x}_\ell(2k+1) = \begin{bmatrix} s_\ell(2k+1) \\ s_\ell^*(2k) \end{bmatrix}.$$

The proposal also supports STBC encoding of two input streams of modulation symbols in parallel. In this case the two input streams can be expressed as a vector of modulation symbols,

$$\mathbf{s}_\ell(n) = \begin{bmatrix} s_\ell^0(n) \\ s_\ell^1(n) \end{bmatrix},$$

and the output of the STBC processing is

$$\mathbf{x}_\ell(2k) = \begin{bmatrix} s_\ell^0(2k) \\ -s_\ell^{0*}(2k+1) \\ s_\ell^1(2k) \\ -s_\ell^{1*}(2k+1) \end{bmatrix} \text{ and } \mathbf{x}_\ell(2k+1) = \begin{bmatrix} s_\ell^0(2k+1) \\ s_\ell^{0*}(2k) \\ s_\ell^1(2k+1) \\ s_\ell^{1*}(2k) \end{bmatrix}.$$

This processing takes place in all 52 data subcarriers of the 20 MHz OFDM symbol and all 108 data subcarriers of the 40 MHz OFDM symbol.

11.2.2.3 Antenna mapping of STBC encoded spatial streams

The STBC processing is applied only to the OFDM symbols in the HT-Data portion of the PPDU. The pilot subcarriers in the HT-Data portion are transmitted as they normally would be for either direct-mapped or spatial spreaded operation. This is illustrated below in Figure 47, which shows preamble and pilot insertion subsequent to the STBC encoding. A normal packet using STBC will include N_{STS} HT-LTF symbols.

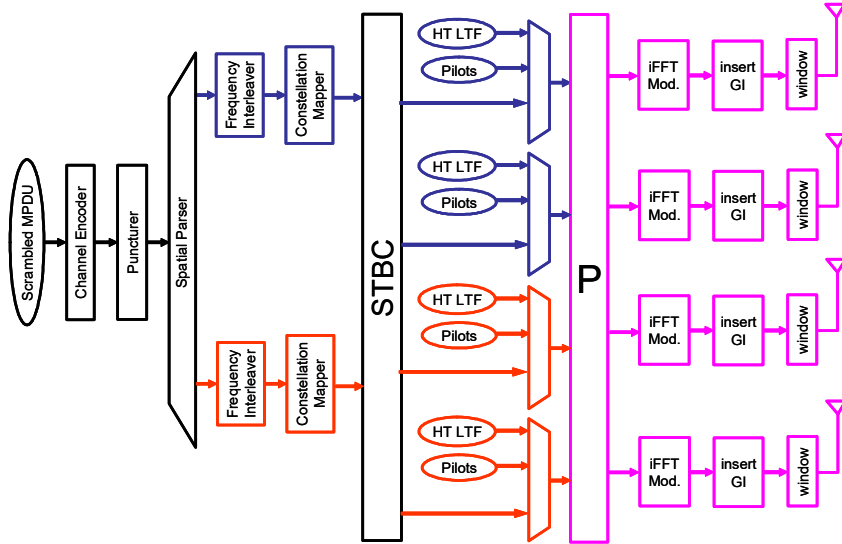


Figure 47: Example of antenna mapping of STBC encoded spatial streams

11.2.2.4 HT-Short Training Field in STBC mode

HT-STF is identical to basic MIMO case (refer to section 11.2.1.5.3). The HT-STF is transmitted as it would be for normal direct mapped operation, when the STBC output is direct mapped to the transmit antennas, or as it would be for normal spatial spreading operation when the STBC output is applied to the transmit antennas through a spatial spreading $\mathbf{P}$ matrix.

11.2.2.5 HT-Long Training Field in STBC mode

HT-LTFs are identical to the basic MIMO case (refer to section 11.2.1.5.4). The HT-LTF is transmitted as it would be for normal direct mapped operation, when the STBC output is direct mapped to the transmit antennas, or as it would be for normal spatial spreading operation when the STBC output is applied to the transmit antennas through a spatial spreading $\mathbf{P}$ matrix. A normal packet using STBC will include N_{STS} HT-LTF symbols.

11.2.2.5.1 MIMO Channel sounding

MIMO channel sounding in STBC mode is identical to that of basic MIMO. Sounding packets can be sent in STBC mode, in which case the number of HT-LTF symbols may be greater than N_{STS} .

11.2.2.6 MCS field in STBC mode

MCS set for STBC is identical to that of basic MIMO, as described in section 11.2.1.6.2.2.

11.2.2.6.1 Pad bits (PAD)

The length of the message is extended so that it becomes a multiple of the number of data bits per OFDM symbol for each data (spatial) stream. When operating in STBC mode, the length of the message is further extended so that the number of OFDM symbols is even. The number of Pad bits is dependent on how the bits are divided over the spatial streams.

11.2.2.7 Puncturing of Coded Data in STBC mode

STBC uses the same puncturing pattern as the basic MIMO mode, described in 11.2.1.7.6.

11.2.2.8 MCS set in STBC mode

MCS 0 through MCS 15, MCS 32, and MCS 33 through MCS 43 (see Table 17) may be used with STBC.

11.2.3 Transmit Beamforming (Optional Mode)

11.2.3.1 Introduction

One method of improving the SNR at the receiver, for a given distance between stations, is to apply transmit beamforming. A basic requirement for transmit beamforming is the availability of channel state information (CSI). In our proposal, CSI is obtained by assuming channel reciprocity. The initiator sends a TRQ, which is a request for a sounding PPDU, to the intended recipient. The recipient may send a sounding packet back to the initiator, however this is optional. The initiator extracts the CSI from this packet, and uses the CSI to compute transmit steering vectors for the forward channel.

While support for the transmission and reception of extension LTFs is optional, the additional CSI that they allow a TxBF capable STA to obtain can significantly improve performance. It is recommended that the recipient of a TRQ should respond with a sounding PPDU, and that this PPDU should contain extension LTFs if $N_{STS} \leq N_{TX}$.

This successful application of this process depends on the presumption that the forward channel is reciprocal to the reverse channel. This presumption relies on calibrated RFs to compensate for imbalances between the gain and phase responses of the transmit and receive RF chains in a STA. Our proposal also includes a packet exchange sequence to enable calibration of RF chains at a STA.

While support for the calibration protocol is not mandatory, any STA that supports transmit beamforming should also implement support for calibration in order to ensure reliable reception of beamformed PPDU that it transmits. A STA that does not support transmit beamforming does not need to implement calibration in order to ensure reliable reception of beamformed PPDU that are directed to it.

11.2.3.2 Motivation of MIMO-Beamforming (Informative)

Beamforming-MIMO can achieve higher throughput than basic MIMO at the same SNR, or conversely, higher range at the same data rate. The benefit of TX beamforming is most pronounced when the number of TX antennas is larger than the RX antennas, when multiple spatial streams are being transmitted. For e.g., a typical configuration involving TX beamforming could be either 3 or 4 antennas at the AP, and 2 antennas at the client. Hence, the client is kept low-cost, while the AP shoulders a higher cost burden.

11.2.3.3 Description of BF-MIMO

11.2.3.3.1 Beamformed PPDU

The transmitter may choose to use antenna beamforming in order to increase the antenna gain in the direction of an intended receiver. The beamforming process is represented mathematically as a linear transformation, mapping the streams of data to the transmit antennas.

Let x be the N_{SS} dimensional vector of data, where each element of x is from one of the spatial streams of data. The beamforming transformation is represented by a $N_{TX} \times N_{SS}$ matrix, V . The beamforming operation, on a per subcarrier basis, is represented by,

$$y_{N_{TX} \times 1} = V_{N_{TX} \times N_{SS}} \cdot x_{N_{SS} \times 1} \quad (61)$$

The y vector is an N_{TX} dimensional vector whose elements get mapped to the N_{TX} antennas. The beamforming matrix V is applied to the HT-STF and HT-LTF training fields as well as the data. There are several methods for calculating V . One of them involves singular value decomposition (SVD) of the channel transfer matrix H .

It is optional for a device to be able to perform TX beamforming.

11.2.3.3.2 MIMO Channel sounding

11.2.3.3.2.1 MIMO Channel sounding principles

MIMO channel measurement takes place in every PPDU as a result of transmitting the HT-LTFs as part of the PLCP preamble. At a minimum, the number of HT-LTFs transmitted must be equal to the number of spatial streams transmitted, and these must be transmitted using the same spatial steering transformation that is used for the HT-Data. This enables the computation of the spatial equalization at the receiver.

When the number of spatial streams, N_{SS} , is less than the number of transmit antennas, sending only N_{SS} HT-LTFs does not allow the receiver to recover a full characterization of the MIMO channel, even though the resulting MIMO channel measurement is sufficient for receiving the HT-Data. However, there are several cases where it is desirable to obtain as full a characterization of the channel as possible, thus requiring the transmission of as many HT-LTFs as an STA is willing to send, subject to $N_{LTF} \leq N_{TX}$. We refer to these cases of MIMO channel measurement as MIMO channel sounding, and the PPDU carrying extension HT-LTFs should be sounding PPDU, identified by the appropriate bit being set in HT-SIG.

11.2.3.3.2.1.1 Sounding PPDU for calibration

In the case of a bidirectional calibration exchange, two STAs exchange sounding PPDU enabling the receiving STA to compute an estimate of the MIMO channel matrix, $\mathbf{H}^{(k)}$, for each subcarrier. In general, in an exchange of calibration messages, the number of spatial streams will be less than the number of transmit antennas, necessitating the use of segmented-LTFs. Particularly when a small number of spatial streams is used for transmitting HT-Data, it is therefore recommended that spatial spreading be used for the HT-Data portion of the PPDU, so that the spatial spreading transmit steering will also be used for the HT-LTFs.

11.2.3.3.2.1.2 Sounding PPDU for channel quality assessment

A MIMO channel with N_{Tx} transmit antennas and N_{Rx} receive antennas can support a maximum of $N_{SS,max} = \min(N_{Tx}, N_{Rx})$ spatial streams. In order for a receiving STA to obtain a channel quality assessment for all $N_{SS,max}$ available spatial streams when using a transmit steering matrix $\mathbf{P}^{(k)}$, it needs an estimate of the effective channel $\mathbf{H}^{(k)}\mathbf{P}^{(k)}$, where $\mathbf{P}^{(k)}$ is in this case a $N_{Tx} \times N_{SS,max}$ orthonormal steering matrix. This requires the transmitting STA to send $N_{SS,max}$ HT-LTFs, using the tone interleaved columns of $\mathbf{P}^{(k)}$. If an STA supports the transmission of segmented-LTFs it can send a sounding PPDU containing $N_{SS,max}$ HT-LTFs, comprising N_{SS} data HT-LTFs and $N_{SS,max} - N_{SS}$ extension HT-LTFs. If an STA does not support segmented-LTFs then a channel quality assessment can still be conducted, however the quality of the assessment will be reduced.

11.2.3.3.2.1.3 Sounding PPDU for transmit steering computation

In order to compute transmit steering vectors through either eigenvalue decomposition or singular value decomposition, a transmitting STA must in general have a good estimate of the channel matrix, $\mathbf{H}^{(k)}$, for each subcarrier of the channel over which it is transmitting. The STA computing transmit steering vectors can obtain this estimate if the STA to which it intends to transmit sends it a sounding PPDU that allows it to estimate $\mathbf{H}_R^{(k)} = \left(\mathbf{H}_F^{(k)}\right)^T$ (assuming channel reciprocity is in effect), where $\mathbf{H}_R^{(k)}$ is the reverse channel, which is the channel over which the HT-LTFs were transmitted, and $\mathbf{H}_F^{(k)}$ is the forward channel, which is the channel for which the transmit steering vectors are being computed. The format of the sounding PPDU may be either direct-mapped, spatially spread, or beamformed.

The description below assumes that the STAs support segmented-LTFs. If this is not the case, then an STA will not be able to send PPDU containing N_{Tx} HT-LTFs unless $N_{STS} = N_{Tx}$. In this situation the calculated transmit steering vectors will be sub-optimal.

If the HT-LTF is transmitted in direct-mapped format, then it should contain N_{Tx} HT-LTFs, and the receiver may then obtain a direct estimate of the channel matrices $\mathbf{H}_R^{(k)}$ from which it may compute an SVD or the eigenvalue decomposition of $\mathbf{R}_F^{(k)} = \left(\mathbf{H}_F^{(k)}\right)^H \mathbf{H}_F^{(k)} = \left(\mathbf{H}_R^{(k)}\right)^* \left(\mathbf{H}_R^{(k)}\right)^T$.

If the HT-LTF is transmitted in spatially spread mode, then it should also contain N_{Tx} HT-LTFs. The receiver may obtain a direct estimate of $\mathbf{H}_F^{(k)}$ by right multiplying its estimate of the effective channel, $\mathbf{H}_R^{(k)} \mathbf{P}^{(k)}$, by $\left(\mathbf{P}^{(k)}\right)^H$. Alternately, the receiver can compute an estimate of $\mathbf{R}_F^{(k)}$ directly, since $\left(\mathbf{H}_R^{(k)} \mathbf{P}^{(k)}\right)^* \left(\mathbf{H}_R^{(k)} \mathbf{P}^{(k)}\right)^T = \left(\mathbf{H}_R^{(k)}\right)^* \left(\mathbf{H}_R^{(k)}\right)^T = \mathbf{R}_F^{(k)}$, since $\mathbf{P}^{(k)}$ is in this case an $N_{Tx,R} \times N_{Tx,R}$ unitary matrix, where the notation $N_{Tx,R}$ refers to the number of transmit antennas on the reverse link.

Finally, if the HT-LTF is transmitted in beamforming mode, so that $\mathbf{P}_R^{(k)} = \mathbf{V}_R^{(k)}$ is the $N_{Tx,R} \times N_{SS,\max}$ matrix of right singular vectors of the reverse channel matrix $\mathbf{H}_R^{(k)}$, then the PPDU only needs to contain $N_{SS,\max} = \min(N_{Tx}, N_{Rx})$ HT-LTFs. The receiver obtains from this

an estimate of the $N_{Rx,R} \times N_{SS,\max}$ equivalent channel matrix $\mathbf{H}_R^{(k)} \mathbf{V}_R^{(k)}$. The receiver can compute from this an estimate of the sample covariance matrix as

$\mathbf{R}_F^{(k)} = \left(\mathbf{H}_R^{(k)} \mathbf{V}_R^{(k)}\right)^* \left(\mathbf{H}_R^{(k)} \mathbf{V}_R^{(k)}\right)^T = \left(\mathbf{H}_R^{(k)}\right)^* \left(\mathbf{H}_R^{(k)}\right)^T$. Even though $\mathbf{V}_R^{(k)}$ is not in general unitary (i.e. it is not, in general, square, since the channel is not symmetrical), this equality holds since $\mathbf{H}_R^{(k)} \mathbf{V}_R^{(k)} = \mathbf{U}_R^{(k)} \mathbf{\Sigma}_R^{(k)}$ and $\left(\mathbf{U}_R^{(k)} \mathbf{\Sigma}_R^{(k)}\right)^* \left(\mathbf{U}_R^{(k)} \mathbf{\Sigma}_R^{(k)}\right)^T = \mathbf{R}_F^{(k)}$.

11.2.3.3.3 Calculation of beamforming matrix using SVD (Informative)

Once a STA has a proper estimate of the channel, then it can use that channel estimate to select a recommended beamforming matrix. There are a variety of techniques that can be used to select the beamforming matrix. One method of selecting the beamforming matrix is by calculating the singular value decomposition of the channel from this STA to the intended receiving STA. Let H be the channel matrix from the transmitter to the receiver. The SVD of the channel matrix is given by,

$$H = UDV^H \quad (62)$$

Both U and V are unitary matrices and D is a diagonal matrix of singular values. The transmitter selects the dominant N_{SS} singular values and then sends only N_{SS} spatial streams. The first N_{SS} rows of the V matrix are used as the beamforming matrix, mapping the spatial streams of data to the TX antennas. This same beamforming matrix is applied to the HT-LTFs, except for one difference. The number of HT-LTFs is equal to N_{ss} , and each transmission of HT-LTF is shaped by one singular vector.

11.2.3.3.3.1 Channel Reciprocity

To determine the beamforming matrix, the transmitter needs to know the channel from the transmitter to the intended receiver. That channel is estimated using implicit feedback and channel reciprocity. The transmitter uses the previous sounding PPDU sent from the intended receiver to estimate the channel from the intended receiver to the transmitter. In order to estimate the channel from the receiver to the transmitter, it uses the principle of reciprocity. The principle of reciprocity is that the downlink channel (the channel from the AP to the STA) is the transpose of the uplink channel (the channel from the STA to the AP). Letting H_D be the downlink channel and H_U be the uplink channel, reciprocity is,

$$H_U = H_D^T \quad (63)$$

11.2.3.3.4 Calibration Methodology (Informative)

11.2.3.3.4.1 Calibration Overview

In order for a transmitting 802.11n STA to transmit to another 802.11n STA using beamforming, it must have a good characterization of the channel that it is transmitting over so that it can choose the correct transmit steering vectors. The STA obtains this characterization by observing the HT-LTF transmitted by the STA to which it is transmitting. This approach is based on the reciprocal property of the over-the-air (antenna-to-antenna) TDD channel, and reciprocity must be in effect for the approach to provide the best rate and range performance available.

Although the Basic MIMO and Walsh-CDD modes do not require it, calibration neither improves nor degrades performance with those modes. Thus, STAs may calibrate upon entering a BSS in which the AP is transmit beamforming capable, or at any other time, and if they are capable of transmitting in beamforming mode, the resulting calibration correction vectors may be employed for all transmission modes and on all frames. STAs that are not capable of transmitting in beamforming mode may also perform the calibration procedure with any transmit beamforming capable AP with which they associate, in order to enable that AP to transmit to them in beamforming mode.

Throughout the discussion of beamforming transmission in this document, it is assumed that communication in beamforming mode takes place between devices that have been calibrated.

The following section describes the calibration procedure for a communication link, where the two communicating STAs are referred to as STA A and STA B. Note: calibration as described here is only applicable to STAs with two or more antennas, where both transmission and reception are possible on each antenna.

11.2.3.3.4.2 Calibration procedure for Tx Corrections

In order to consider the operation of a TDD MIMO OFDM system in conjunction with beamforming techniques through transmit and receive steering, it is necessary to first consider the need to ensure that the over-the-air reciprocity of the TDD channel is preserved in the observed, baseband-to-baseband TDD channel. Reciprocity is critical in the functioning of these systems because it provides efficient means for a STA to learn the transfer function of the channel over which it will transmit.

In order to ensure that the baseband-to-baseband channel seen by the spatial processing engines is reciprocal, it is necessary to calibrate the STA radio to correct the differences in phase and amplitude response in the transmit and receive chains.

The reciprocity of the over-the-air TDD MIMO channel can be expressed as a transpose relationship between the channel response matrices associated with forward and reverse channels between two STAs. Consider, for example, STA A and STA B, where we will refer to the channel over which STA A transmits as the forward link, and the channel over which STA B transmits as the reverse link. Thus we will define the following two gain matrices for the over-the-air channels (the over-the-air channel is the complex baseband channel that would be realized if the transmitter and receiver responses have ideal constant gain and zero phase across the channel bandwidth):

- $\mathbf{H}_{A \rightarrow B}(\ell)$: forward link gain matrix for subcarrier ℓ
- $\mathbf{H}_{B \rightarrow A}(\ell)$: reverse link gain matrix for subcarrier ℓ ,

The reciprocal relationship between these two channels is expressed as:

$$\mathbf{H}_{B \rightarrow A}(\ell) = \mathbf{H}_{A \rightarrow B}^t(\ell).$$

The observed channels, however, are effected by the amplitude and phase responses of the transmit and receive chains. Assuming good isolation, these can be expressed as diagonal matrices with complex valued diagonal entries, of the form $\mathbf{C}_{A,Tx}(\ell)$. The relationship between the observed channels, $\tilde{\mathbf{H}}_{A \rightarrow B}(\ell)$ and $\tilde{\mathbf{H}}_{B \rightarrow A}(\ell)$, and the over-the-air channel is

$$\tilde{\mathbf{H}}_{A \rightarrow B}(\ell) = \mathbf{C}_{B,Rx}(\ell) \mathbf{H}_{A \rightarrow B}(\ell) \mathbf{C}_{A,Tx}(\ell), \text{ and}$$

$$\tilde{\mathbf{H}}_{B \rightarrow A}(\ell) = \mathbf{C}_{A,Rx}(\ell) \mathbf{H}_{B \rightarrow A}(\ell) \mathbf{C}_{B,Tx}(\ell).$$

The resulting observed channels are not, in general, reciprocal. However, through a simple channel sounding procedure that involves an exchange of training sequences, correction vectors

can be calculated that are applied on transmit to restore reciprocity. The resulting calibration is quite stable and needs to be updated infrequently, typically on association.

The object of the procedure is to compute correction vectors $\mathbf{K}_A(\ell)$ and $\mathbf{K}_B(\ell)$ that restore reciprocity such that

$$\tilde{\mathbf{H}}_{A \rightarrow B}(\ell) \mathbf{K}_A(\ell) = [\tilde{\mathbf{H}}_{B \rightarrow A}(\ell) \mathbf{K}_B(\ell)]^t.$$

The correction vectors are applied on transmit in such a way that each element in the correction vector scales the transmit vector element associated with a specific antenna. Given a modulation symbol vector, $\mathbf{s}_A(\ell)$, in subcarrier ℓ at STA A, and beamforming matrix $\mathbf{V}(\ell)$, then the transmitted vector in subcarrier ℓ is given by $\mathbf{x}(\ell) = \mathbf{K}_A(\ell) \mathbf{V}_A(\ell) \mathbf{s}_A(\ell)$.

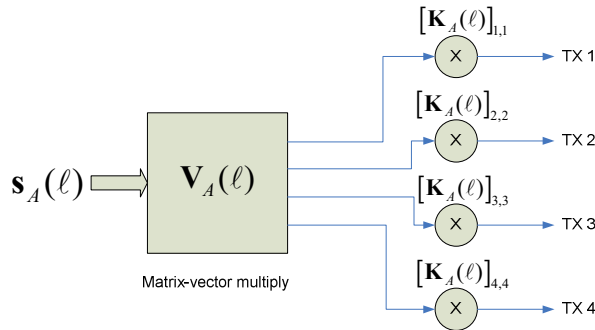


Figure 48: Application of calibration correction vector on Tx

Correction vectors that will satisfy this relationship are given by:

$$\mathbf{K}_A(\ell) = (\mathbf{C}_{A,Tx}(\ell))^{-1} \mathbf{C}_{A,Rx}^t(\ell), \text{ and}$$

$$\mathbf{K}_B(\ell) = (\mathbf{C}_{B,Tx}(\ell))^{-1} \mathbf{C}_{B,Rx}^t(\ell).$$

Calibration can also be applied on receive in a similar manner. Tx calibration only is addressed here.

For STAs that support only 20 MHz operation, calibration must be performed for subcarriers with indices between -26 and 26, except for the subcarrier with index 0. For STAs supporting both 20 MHz and 40 MHz operation, calibration must be performed for subcarriers with indices between -58 and 58, except for the subcarriers with indices -1, 0, and 1.

The calibration procedure is as follows:

1. STA A transmits a Calibration Training message, initiating the calibration procedure.

-
- 1 2. STA B transmits a Calibration Training message, which includes the HT-LTF that allows a
2 receiving STA A to estimate the channel matrices $\mathbf{H}_{B \rightarrow A}(\ell)$.
 - 3 3. STA A transmits a Calibration Training message, which includes the HT-LTF that allows
4 STA B to estimate the channel matrices $\mathbf{H}_{A \rightarrow B}(\ell)$.
 - 5 a. The previous two steps must occur over a sufficiently short time interval that the
6 channel does not change over the interval.
 - 7 4. STA A computes an estimate of $\mathbf{H}_{B \rightarrow A}(\ell)$ based on the received HT-LTF.
 - 8 5. STA B computes an estimate of $\mathbf{H}_{A \rightarrow B}(\ell)$ based on the received HT-LTF.
 - 9 6. STA B sends the quantized estimates of $\mathbf{H}_{A \rightarrow B}(\ell)$ to STA A using the Calibration
10 Measurement Message that contains the Channel Measurement Report.
 - 11 7. STA A uses the estimates of $\mathbf{H}_{B \rightarrow A}(\ell)$ and $\mathbf{H}_{A \rightarrow B}(\ell)$ to compute the correction vectors
12 $\mathbf{K}_A(\ell)$ and $\mathbf{K}_B(\ell)$.
 - 13 8. STA A sends the quantized correction vectors $\mathbf{K}_B(\ell)$ to STA B using the Calibration
14 Correction Vector Message that contains the Correction Vector element.
 - 15 9. STA A and STA B now have correction vectors and are considered to be calibrated.
 - 16 Once a STA has completed the calibration procedure, the correction vectors, $\mathbf{K}(\ell)$, are assumed
17 to be available at the STA's transmitter, and are incorporated into the transmit spatial processing
18 procedure for all subsequent communications.
 - 19 This procedure needs to be performed only once for any STA that will participate in a
20 beamforming exchange with another STA. For example, once an AP performs this procedure
21 with one STA, it is calibrated and may participate in a beamforming exchange with any other
22 calibrated STA. However, in many networks, the AP will be the primary agent for calibrating
23 client STAs. Thus a typical AP will participate in many of these calibration procedures.

24 11.2.3.3.4.3 Calibration for Beamforming Rx-only STAs

25 STAs that have no transmit beamforming capabilities, but that still are capable of receiving
26 beamforming transmissions, are referred to as Rx-only STAs. Such STAs may participate in a
27 calibration procedure similar to that described above. However, it is not necessary for such a
28 STA to have calibrated RFs in order to reliably receive PPDU's that are transmitted to it using Tx
29 beamforming.

31 11.2.3.3.4.4 Calibration Processing

32 The MIMO calibration training sequence consists of $N_{\text{CAL}} = N_{\text{Tx}}$ HT-LTFs. The HT-LTF for the
33 first stream consists of an 800 ns guard interval followed by two periods of a 3.2 μs training
34 symbol sequence, for a total duration of 7.2 μs . The HT-LTF for the second, third, and fourth
35 stream, if exist, consists of an 800 ns guard interval followed by one periods of a 3.2 μs training

symbol sequence, for a total duration of 4.0 μ s. For details on the format of the HT-LTF, see section 11.2.1.5.4.

11.2.3.3.5 HT-Short Training Field in BF-MIMO mode

HT-STF is identical to basic MIMO case (refer to section 11.2.1.5.3). The HT-STF undergoes the same spatial steering as the DATA.

11.2.3.3.6 HT-Long Training Field in BF-MIMO mode

HT-LTFs are identical to the basic MIMO case (refer to section 11.2.1.5.4). The HT-LTF undergoes the same spatial steering as the DATA.

11.2.3.3.7 MCS field in BF-MIMO mode

MCS set for BF-MIMO is identical to that of basic MIMO, as described in section 11.2.1.6.2.2.

11.2.3.3.8 Antenna streams / Transmitter architecture in BF-MIMO mode

The only difference in the transmitter architecture with respect to the basic MIMO mode is the introduction of the spatial steering matrix, as shown in Figure 49:

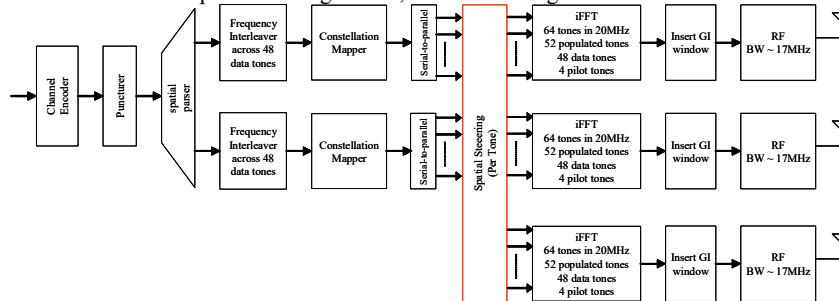


Figure 49: Transmitter architecture for TX Beamforming for $N_{ss}=2$, and $N_{TX} = 3$

11.2.3.3.9 Puncturing of Coded Data in BF-MIMO mode

TX Beamforming uses the same puncturing pattern as the basic MIMO mode, described in 11.2.1.7.6.

11.2.3.3.10 MCS set in BF-MIMO mode

Any MCS (see Table 17) in the mandatory MCS set or the optional MCS set may be used in BF-MIMO. A station intending to transmit using any optional MCS (those with indices above 15) must establish support of the optional MCS at the receiving STA.

11.2.3.3.11 Power Loading of spatial streams in BF-MIMO

All spatial streams in the BF-MIMO mode are transmitted at the same power level.

11.2.4 Low-Density Parity-Check Coding (Optional Mode)

Optional Low-Density Parity-Check (LDPC) coding may be used with all MCS 0-126 from Table 17. When encoding specified in this clause is applied, convolutional encoder and its associated puncturing and padding shall not be used.

11.2.4.1 Code Rates and Codeword Lengths

Code rate (R) of the LDPC code may be selected from the set of code rates defined for mandatory convolutional codes (1/2, 2/3, 3/4 and 5/6). One of three codeword sizes is used to encode packets. Codeword size in bits, N, may be 576, 1152, or 1728.

11.2.4.2 PPDU Encoding using LDPC Codes

This subclause, which specifies the LDPC encoding, replaces corresponding procedure defined for mandatory convolutional codes.

LDPC codes are block codes that are specified by the parity check matrix of size $M \times N$, which defines an LDPC block code (N,K), where K is the information block size in bits, N is the length of the codeword, and M is the number of parity check bits, $M=N-K$. Code rate is defined as $R=K/N$. The general characteristic of an LDPC parity check matrix is a low density of non-zero elements (1's in this case), which allows utilization of efficient decoding algorithms. LDPC parity check matrix is designed in a way that enables simple encoding as well. It can be represented in the following form:

$$\mathbf{H} = [\mathbf{H}^d \mid \mathbf{H}^p]$$

$\mathbf{H}^d$ is an $M \times K$ matrix and corresponds to the “data” bits of the codeword. The design of this matrix ensures high coding gain. $\mathbf{H}^p$ is an $M \times M$ modified “dual diagonal” matrix, which corresponds to the “parity” bits of the codeword. LDPC codes applied here are systematic and canonic block codes. Codewords have the following structure:

$$\mathbf{c} = \begin{bmatrix} \mathbf{d} \\ \mathbf{p} \end{bmatrix}$$

where $\mathbf{d} = [d_0, d_1, \dots, d_{K-1}]^T$ is the block of (uncoded) data bits and $\mathbf{p} = [p_0, p_1, \dots, p_{M-1}]^T$ are the parity bits. A codeword is any binary N-vector $\mathbf{c}$ that satisfies:

$$\mathbf{H}\mathbf{c} = \mathbf{H}^d\mathbf{d} + \mathbf{H}^p\mathbf{p} = \mathbf{0}.$$

Since the information packet size may not in general be a multiple of number of information bits per codeword, procedure for encoding is defined in this subclause. Based on the MCS, following two parameters are derived first:

$$N_{CBPS} = N_{SD} \times \sum_{i_{ss}=1}^{N_{ss}} N_{BPSC-i_{ss}}, \text{ number of coded bits per OFDM symbol}$$

```

1      NDBPS = NCBPS × R, number of information bits per OFDM symbol
2
3      where: NBPSCiss is the number of coded bits per sub-carrier in iss spatial stream, NSD is
4      the number of data sub-carriers, and NSS is the number of spatial streams.
5
6  Both shortening (padding the payload with zeros before encoding and removing those extra zero
7  bits from transmission), and puncturing (reduction of number of bits of the codeword prior to
8  transmission) may be applied in order to ensure minimum overhead without degrading
9  performance.
10
11 HTLENGTH parameter in HT_SIGNAL field is calculated based on the value of two
12 TXVECTOR array parameters: A-MPDU and HT_LENGTH, as follows:
13
14 if A-MPDU == 0
15     HTLENGTH = HT_LENGTH
16 else
17     if(NDBPS ≤ 234)
18         NOFDM = ceiling (HT_LENGTH × 8/ NDBPS) +1
19     else
20         NCWORDS_MIN = ceiling (HT_LENGTH × 8/(1728 × R))
21         NSHORTENING = NCWORDS_MIN × 1728 × R – HT_LENGTH × 8
22         NOFDM = ceiling ((NCWORDS_MIN × 1728 – NSHORTENING) / NCBPS)
23     end
24     HTLENGTH = 110000000000b + NOFDM
25 end
26
27 This means that in the non-A-MPDU mode the HTLENGTH field specifies the number of octets
28 in the PSDU, whereas in the A-MPDU mode, the HTLENGTH field (bits 0 through 9) specifies
29 the number of transmitted OFDM symbols in the data mode.
30
31 The encoding procedure uses the following parameters as input:
32
33     HTLENGTH – containing the information as described in the previous paragraph
34     MCS – modulation type and code rate set
35
36 The procedure for encoding consists of the following steps:
37
38 a) Based on the contents of HTLENGTH, compute the following parameters:
39
40 if (the two MSBs of HTLENGTH are NOT 11b) // non-A-MPDU mode
41
42     NINFO_BITS = HTLENGTH × 8
43     NOFDM_MIN = ceiling (NINFO_BITS / NDBPS)
44     NCWORDS = ceiling (NINFO_BITS / (1728 × R))
45     n1 = ceiling (((NINFO_BITS / R) / NCWORDS) / 576)
46     n2 = floor ((NCBPS × NOFDM_MIN – NINFO_BITS) / (576 × (1-R) × NCWORDS))
47     N = max(n1, min(3,n2)) × 576
48     K = N × R, M = N - K
49 else // A-MPDU mode

```

```

1      if (NDBPS <= 234)
2          NOFDM = HTLENGTH (bits 0 through 9)
3          NINFO_BITS = (NOFDM - 1) × NDBPS
4          NCWORDS = ceiling (NINFO_BITS / (1728 × R))
5          n1 = ceiling (((NINFO_BITS / R) / NCWORDS) / 576)
6          n2 = floor ((NCBPS × NOFDM - NINFO_BITS) / (576 × (1-R) × NCWORDS))
7          N = max(n1, min(3, n2)) × 576
8          K = N × R, M = N - K
9      else
10         N = 1728, K = N × R, M = N - K
11         if (rem (NOFDM × NCBPS, N) > M)
12             NCWORDS = ceiling (NOFDM × NCBPS / N)
13         else
14             NCWORDS = floor (NOFDM × NCBPS / N)
15         end
16         NINFO_BITS = min (NOFDM × NDBPS, NOFDM × NCBPS - NCWORDS × M,
17             NCWORDS × K)
18     end
19 end
20
21 b) In non-A-MPDU mode, extra OFDM symbols may be added to guarantee performance of
22 punctured LDPC code. The algorithm below determines the optimum number of OFDM
23 symbols, NOFDM based on following performance parameters:
24
25     – Shortening to puncturing ratio, defined as  $SP_{RATIO} = (1-R)/R \times N_s/N_p$ , where  $N_s$ 
26       is number of shortened bits, and  $N_p$  is number of punctured bits for a transmission
27       of current PSDU. Minimum shortening to puncturing ratio is set to  $SP_{RATIO\_MIN} =$ 
28       1.2
29     – Maximum number of extra OFDM symbols allowed is set to  $NOFDM\_EXTRA\_MAX =$ 
30       2
31
32      $N_{PARITY\_BITS} = \text{ceiling} (NCWORDS \times M - (1/ SP_{RATIO\_MIN}) \times ((1-R)/R) \times$ 
33        $(NCWORDS \times K - NINFO\_BITS))$ 
34      $NOFDM = \text{min} (\text{ceiling} (NINFO\_BITS / NDBPS) + NOFDM\_EXTRA\_MAX,$ 
35        $\text{ceiling} ((N_{PARITY\_BITS} + NINFO\_BITS) / NCBPS));$ 
36
37 c) For each of the codewords of length N determine amount of the information bits to encode,
38  $K_1 \leq K$ , as well as the number of parity check bits to be transmitted,  $M_1 \leq M$ . This, in turn,
39 determines by how many bits to shorten the information portion of the codeword  $N_{SHORTEN\_CW}$ ,
40 as well as by how many bits to puncture a codeword,  $N_{PUNCTURE\_CW}$ . In some cases it may be
41 required that the last codeword has different number of data and parity bits,  $K_{1\_LAST}$  and  $M_{1\_LAST}$ 
42 , respectively, (and consequently  $N_{SHORTEN\_CW\_LAST}$  and  $N_{PUNCTURE\_CW\_LAST}$ ) than the other
43 codewords.
44 The calculations below also ensure that the last codeword may only be shortened more than
45 others, and punctured less than others.
46
47      $K_1 = \text{ceiling} (NINFO\_BITS / NCWORDS)$ 
48      $N_{PARITY\_BITS} = \text{min} (NCWORDS \times M, NOFDM \times NCBPS - NINFO\_BITS)$ 
49      $M_1 = \text{min} (M, \text{floor} (N_{PARITY\_BITS} / NCWORDS))$ 

```

```

1       $K_{1\_LAST} = N_{INFO\_BITS} - K_1 \times (N_{CWORDS} - 1)$ 
2       $M_{1\_LAST} = \min(M, N_{PARITY\_BITS} - M_1 \times (N_{CWORDS} - 1))$ 
3
4       $N_{SHORTEN\_CW} = K - K_1$ 
5       $N_{SHORTEN\_CW\_LAST} = K - K_{1\_LAST}$ 
6       $N_{PUNCTURE\_CW} = M - M_1$ 
7       $N_{PUNCTURE\_CW\_LAST} = M - M_{1\_LAST}$ 
8
9  d) For A-MPDU mode only, calculate information bits padding,  $N_{PADDING\_INFO}$ .
10
11  The number of zero bits,  $N_{PADDING\_INFO}$ , concatenated to the information bits and passed through
12  the scrambler is calculated the following way:
13
14       $N_{PADDING\_INFO} = N_{INFO\_BITS} - HT\_LENGTH \times 8$ 
15
16  e) Last OFDM symbol padding field parameter computation
17
18  If the total number of coded bits doesn't fit integer number of OFDM symbols, then additional
19  padding (scrambled zeros) bits are added to the last OFDM symbol. Number of those bits,
20   $N_{PAD\_OFDM\_LAST}$ , is computed as follows:
21
22       $N_{PAD\_OFDM\_LAST} = N_{OFDM} \times N_{CBPS} - (N_{INFO\_BITS} + M_1 \times (N_{CWORDS} - 1) + M_{1\_LAST})$ 
23
24  f) LDPC encoding
25
26  Generate all  $N_{CWORDS}$  codewords by applying any of the encoding methods, such that  $\mathbf{H}\mathbf{c}_i = \mathbf{0}$ ,
27  where  $i=0, 1, \dots, N_{CWORDS}-1$  with shortening and puncturing as necessary.  $\mathbf{H}$  is the parity check
28  matrix for the selected codeword size and code rate. Only one  $\mathbf{H}$  matrix is used for the entire
29  packet. The information vector for the  $i$ -th codeword to be encoded is formed by concatenating
30   $K_1$  scrambled bits, which include information bits and optional  $N_{PADDING\_INFO}$  zeros - (denoted as
31   $z$ 's below, last codeword, A-MPDU mode only), and  $N_{SHORTEN\_CW} = K - K_1$  zeros:
32
33      
$$\mathbf{d}^i = [\underbrace{d_0^i, d_1^i, \dots, d_{K_1-1}^i}_{K}, \underbrace{0, 0, \dots, 0}_{N_{SHORTEN\_CW}}]^T \quad // \text{non- A-MPDU mode}$$

34
35      
$$\mathbf{d}^i = [\underbrace{d_0^i, d_1^i, \dots, d_n^i, z_{n+1}^i, z_{n+2}^i, \dots, z_{K_1\_LAST-1}^i}_{K}, \underbrace{0, 0, \dots, 0}_{N_{SHORTEN\_CW}}]^T \quad // \text{A-MPDU mode, last codeword}$$

36
37  After the encoding, obtained codeword is punctured (if necessary) by removing the last
38   $N_{PUNCTURE\_CW}$  bits:
39
40      
$$\mathbf{c}^i = [\underbrace{d_0^i, d_1^i, \dots, d_{K_1-1}^i}_{K}, \underbrace{0, 0, \dots, 0}_{N_{SHORTEN\_CW}}, \underbrace{p_0^i, p_1^i, \dots, p_{M_1-1}^i}_{M}, \underbrace{p_{M_1}^i, p_{M_1+1}^i, \dots, p_{M-1}^i}_{N_{PUNCTURE\_CW}}]^T$$

41      
$$// \text{A-MPDU mode, last codeword}$$


```

$$\mathbf{c}^i = [\underbrace{d_0^i, d_1^i, \dots, d_n^i, z_{n+1}^i, z_{n+2}^i, \dots, z_{K_1_LAST-1}^i}_{K_1}, \underbrace{0, 0, \dots, 0}_{N_{SHORTEN_CW}}, \underbrace{p_0^i, p_1^i, \dots, p_{M_1-1}^i, p_{M_1}^i, p_{M_1+1}^i, \dots, p_{M-1}^i}_{M}]^T$$

Shortened and punctured bits are not transmitted over the air. Rather, a concatenation of K_1 data bits and M_1 parity bits is transmitted only:

// non- A-MPDU mode

$$\mathbf{c}_{transmit}^i = [\underbrace{d_0^i, d_1^i, \dots, d_{K_1-1}^i}_{K_1}, \underbrace{p_0^i, p_1^i, \dots, p_{M_1-1}^i}_{M_1}]^T$$

// A-MPDU mode, last codeword

$$\mathbf{c}_{transmit}^i = [\underbrace{d_0^i, d_1^i, \dots, d_n^i, z_{n+1}^i, z_{n+2}^i, \dots, z_{K_1_LAST-1}^i}_{K_1_LAST}, \underbrace{p_0^i, p_1^i, \dots, p_{M_1-1}^i}_{M_1_LAST}]^T$$

g) Codeword and the last OFDM symbol padding field concatenation

Concatenate N_{CWORDS} codewords and $N_{PAD_OFDM_LAST}$ padding bits (denoted as q's below) to form a vector of bits to be transmitted:

// non- A-MPDU mode

$$\mathbf{c}_{transmit} = [d_0^0, \dots, d_{K_1-1}^0, p_0^0, \dots, p_{M_1-1}^0, \dots, d_0^{N_{CWORDS}-1}, \dots, d_{K_1_LAST-1}^{N_{CWORDS}-1}, p_0^{N_{CWORDS}-1}, \dots, p_{M_1_LAST-1}^{N_{CWORDS}-1}, q_0, \dots, q_{N_{PAD_OFDM_LAST}-1}]^T$$

// A-MPDU mode

$$\mathbf{c}_{transmit} = [d_0^0, \dots, d_{K_1-1}^0, p_0^0, \dots, p_{M_1-1}^0, \dots, d_0^{N_{CWORDS}-1}, \dots, d_{K_1_LAST-1}^{N_{CWORDS}-1}, p_0^{N_{CWORDS}-1}, \dots, p_{M_1_LAST-1}^{N_{CWORDS}-1}, q_0, \dots, q_{N_{PAD_OFDM_LAST}-1}]^T$$

Bit d_0^0 is transmitted first.

11.2.4.3 Parity Check Matrices

Parity check matrices $\mathbf{H}$ used in Step c) of the encoding procedure, described in sub-clause 11.2.4.2, are derived from one of the "base" parity check matrices, $\mathbf{H}_b$, specified below. One base matrix is defined per code rate. Size of a base parity check matrix is denoted as $M_b \times N_b$. N_b , the number of columns in the base matrix, is fixed for all code rates, $N_b=24$. M_b , the number of rows in the base matrix, depends on the code rate as follows: $M_b = N_b(1-R)$. Parity check matrix $\mathbf{H}$ of size $M \times N$ is generated by expanding the base matrix for the selected rate, $\mathbf{H}_b$, z -times: $z=N/N_b=M/M_b$. The expansion operation is defined by element values of the base matrix. Each non-negative base matrix element, s , is replaced by a $z \times z$ identity matrix, $\mathbf{I}_z$, cyclically shifted to the right $s' = s \bmod(z)$ times. Each negative number (-1) in the base matrix is replaced by a $z \times z$ zero matrix, $\mathbf{0}_{z \times z}$. For the codeword of size 576 bits, $z = 24$, for codeword of size 1152 bits, $z = 48$, and for the codeword of size 1728 bits, $z = 72$.

Base matrices specification

Rate 1/2: $M_b \times N_b = 12 \times 24$

$$\begin{bmatrix} 0 & 0 & -1 & 0 & -1 & 0 & -1 & -1 & -1 & 0 & -1 & -1 & 1 & 0 & -1 & -1 & -1 & -1 & -1 & -1 & -1 & -1 \\ 29 & -1 & 0 & 26 & -1 & -1 & 0 & -1 & 0 & -1 & -1 & -1 & -1 & 0 & 0 & -1 & -1 & -1 & -1 & -1 & -1 & -1 \end{bmatrix}$$

```

1  -1 -1 -1 21 0 -1 17 -1 -1 38 -1 0 -1 -1 0 0 -1 -1 -1 -1 -1 -1 -1 -1
2  43 -1 -1 30 -1 -1 -1 0 -1 41 0 -1 -1 -1 -1 0 0 -1 -1 -1 -1 -1 -1 -1
3  5 -1 1 -1 -1 20 35 -1 -1 2 -1 -1 -1 -1 -1 -1 0 0 -1 -1 -1 -1 -1 -1
4  -1 46 -1 -1 -1 -1 22 -1 40 8 -1 -1 0 -1 -1 -1 -1 0 0 -1 -1 -1 -1 -1
5  -1 -1 -1 9 -1 -1 18 13 -1 35 -1 27 -1 -1 -1 -1 -1 -1 0 0 -1 -1 -1 -1
6  2 -1 44 -1 -1 -1 27 -1 -1 25 18 -1 -1 -1 -1 -1 -1 -1 0 0 -1 -1 -1 -1
7  33 35 -1 29 -1 -1 16 -1 -1 -1 -1 30 -1 -1 -1 -1 -1 -1 -1 0 0 -1 -1 -1
8  -1 -1 -1 4 4 -1 -1 -1 15 17 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 0 0 -1
9  5 -1 -1 19 -1 14 -1 -1 -1 -1 11 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 0 0
10 10 -1 -1 -1 21 -1 18 8 -1 -1 -1 -1 1 -1 -1 -1 -1 -1 -1 -1 -1 -1 0
11
12

```

Rate 2/3: $M_b \times N_b = 8 \times 24$

```

13 71 40 -1 -1 11 40 -1 -1 -1 69 -1 59 10 -1 -1 21 46 0 -1 -1 -1 -1 -1 -1
14 18 -1 35 51 27 -1 -1 49 17 -1 -1 37 4 -1 -1 -1 -1 0 0 -1 -1 -1 -1 -1
15 42 52 -1 -1 12 -1 54 -1 43 -1 62 62 52 -1 -1 -1 -1 -1 0 0 -1 -1 -1 -1
16 13 -1 27 -1 -1 -1 5 -1 28 33 -1 -1 58 47 18 -1 0 -1 -1 0 0 -1 -1 -1
17 -1 -1 -1 38 50 -1 7 9 34 -1 -1 -1 65 -1 17 70 -1 -1 -1 -1 0 0 -1 -1
18 71 -1 -1 39 62 14 -1 -1 53 -1 39 -1 2 67 -1 -1 -1 -1 -1 -1 -1 0 0 -1
19 54 56 -1 -1 53 -1 -1 2 66 57 -1 -1 -1 24 -1 52 -1 -1 -1 -1 -1 -1 0 0
20 17 -1 44 -1 44 29 -1 -1 48 -1 26 -1 39 -1 14 -1 46 -1 -1 -1 -1 -1 -1 0
21
22

```

Rate 3/4: $M_b \times N_b = 6 \times 24$

```

23
24
25 0 23 -1 -1 0 47 53 1 -1 5 -1 13 66 34 -1 62 65 -1 1 0 -1 -1 -1 -1
26 14 57 7 11 -1 -1 69 -1 25 34 -1 25 13 -1 19 70 -1 35 -1 0 0 -1 -1 -1
27 59 3 -1 18 -1 43 48 58 -1 29 -1 54 49 -1 25 0 66 -1 -1 -1 0 0 -1 -1
28 15 1 2 -1 -1 39 19 -1 37 64 52 -1 28 4 -1 21 20 -1 0 -1 -1 0 0 -1
29 22 64 -1 48 60 -1 36 -1 15 62 68 -1 46 55 -1 41 -1 7 -1 -1 -1 -1 0 0
30 63 36 57 -1 55 -1 41 34 -1 45 46 -1 8 -1 37 44 -1 15 1 -1 -1 -1 -1 0
31
32

```

Rate 5/6: $M_b \times N_b = 4 \times 24$

```

33
34
35 11 26 59 44 36 45 51 32 13 60 3 70 47 21 -1 67 52 49 15 -1 1 0 -1 -1
36 39 58 28 60 43 55 30 51 49 13 50 4 -1 26 10 -1 30 58 28 22 -1 0 0 -1
37 36 11 35 38 1 5 9 36 15 47 -1 39 39 -1 71 53 66 -1 20 45 0 -1 0 0
38 54 67 51 0 15 65 24 17 38 58 53 -1 11 2 2 26 -1 15 -1 6 1 -1 -1 0
39
40

```

(END)

42